KU Leuven

Biomedical Sciences Group
Faculty of Kinesiology and Rehabilitation Sciences
Department of Rehabilitation Sciences

Optimization of vibration training protocols for different populations

Ekaterina Tankisheva

Dissertation presented in partial fulfillment of the requirements for the degree of Doctor in Biomedical Sciences

Promoter: Prof. Dr. Sabine Verschueren

Co-promoter: Prof. Dr. Steven Boonen†

Jury members

Chairman: Prof. Dr. Luc Vanhees

Thesis advisory committee:
Prof. Dr. Christophe Delecluse
Prof. Dr. Ilse Jonkers
Prof. Dr. Harry van Lenthe
Prof. Dr. Ivan Bautmans

2014

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ACKNOWLEDGEMENT

Finally, after four years full of excitement and hard work, this doctoral thesis became real. The way to here was sometimes easy, sometimes difficult, sometimes looked too long. But after all, nothing of this would have happened if I had not had the support of my colleagues, friends and family.

First of all, I would like to thank to my promoters, *Prof. Sabine Verschueren* and *Prof. Steven Boonen*. Dear Sabine, I will always highly appreciate the opportunity which you gave me. You believed in me and you always supported and encouraged me during these years. In the beginning was somehow too difficult but you always stood behind me and always were there when I needed your help. You showed me the way to take decisions and to be independent. I will always be thankful to you.

This project would not have been possible without the incredible help and support of my co-promoter, Prof. Steven Boonen. Dear Prof. Boonen, although, this day was supposed to be one of the happiest day in my life, yet I feel sad. I am sad because you are not here with us to see the end of one successful doctoral project which could not have been possible without you. I really missed your critical but always positive comments and suggestions. Your enthusiasm was so catching and motivating.

Second, I would like to express my great appreciations to *Prof. Luc Vanhees, Prof. Ivan Bautmans, Prof. Christophe Delecluse, Prof. Ilse Jonkers, Prof. Harry van Lenthe*, who were, first of all, my colleagues and then members of my examination committee. Dear Prof. Jonkers, you were the first colleague who I met in the University. To be honest, I started understanding what you were talking about (EMG RMS and Matlab) some weeks later, but your involvement in my studies, your help and collaboration were priceless. Thank you for our meetings during these years and I apologize for the thousands of e-mails with questions which I sent to you. Dear Prof. Delecluse, I appreciate all your explanations about muscle strength and vibrations, about vibration protocols and physical exercises. Dear Prof. van Lenthe, thank you for all your critical questions – to some of them I am still looking for the right answer.

Dear *Prof. Feys*, when I started to write the 'stroke' paper, I was lost. I had some documents with some data and some measurements. You were the one who made the link between all, the one who made this very nice paper publishable. Thank you.

I want to express my appreciation to all my colleagues who were directly involved in my project. Dear *Hans Druyts*, I really do not know what I would do without you. Thank you very much for every time you came to Faber to measure, to install or update a program, to check my results or to re-analyze my data. Your help in my first two papers is indescribable. Dear *Paul Janssen*, despite the inevitable delays, I appreciate your work and your involvement in my project. Thank you for all the vibrators which you repaired and for the times when you came from Geel to Leuven only to explain some additional details unclear to me. I would like to thank to the people who worked in Gasthuisberg as part of this project. Dear *Herman B.*, *Herman P.* and *Walter*, thank you for all the DXA and CT measurements you did for me. Thank you for your attitude and for all the appointments which you gave me, even though, some of them were in the very last moment. I would like to express my special thanks to *Doctor Evelien Gielen*. Dear Evelien, we shared the same promoters and similar problems. I am glad I have a colleague like you. Our talks in the car on our way to the next presentation were irreplaceable.

Dear *An Bogaerts*, I cannot ever thank you enough for everything you did for me. You came back to Faber exactly at the right moment of my doctoral project. I cannot find the words to thank you for everything – for helping me with my study, for sharing your experience with me, for explaining me so many things, for answering all my questions, sometimes more than ones. Thank you for all the chats we had, related or not to work.

Dear *Karen* and *Mariska*, my studies would not have been possible without all your help. Analyzing the EMG with Matlab was one of the most difficult things during my doctoral project. Thank you for all the meetings we had together to discuss either OpenSim or Matlab.

My dear colleagues from room 02.48: *Lotte, Madelon, Armaghan, Bart M., Bart D. and Kurt.* First of all, going to so many wedding parties with you was amazing. Dear Lotte, thank you for all the chats, all the tea and coffee moments in the kitchen. I cannot appreciate enough all your help. Thank you for sharing all your presentations and reports with me. You are a wonderful friend. Dear Madelon, thank you for being the only one who dared to come to Bulgaria for my wedding party. I will never forget the amazing time we spent together in Sofia. Dear Armaghan, you were my best friend here. Thank you for everything – for all the funny moments we had together, for the pizza lunches, for all the troubles we shared, for all the conversations, serious or not so much.

I should mention all the international colleagues who were part of my stay here and without whom I would have not enjoyed it so much – *Farshid*, *Giorgos*, *Snow* and *Zrinka*.

Here is the moment to thank to all my friends who always supported me, although, they had no idea what the topic of my project was but they were always ready to listen to it. Dear *Galina*, you have a special place in my heart and be sure you will always stay there. I cannot thank you enough for the friendship we have. You are my person with a big P. Thank you for always listening to me and my problems. Thank you for the girls' weekends we had – in Barcelona and in France, and for all the dinners in La Terrasse. I am thankful that you are the godmother of my angel, Michail and I cannot find a person who I can trust more about this important job. I would like to thank to *Maria Petrova* for all the lunches in the ALMA and the Flemish lessons we followed together and we enjoyed so much. Dear *Diana*, we have been friends for such a long time and I just don't know how I would have survived without you. Thank you! Dear *Boayn* and *Peter*, our visits in The Hague and Amsterdam were amazing.

Dear *Krisi* and *Gogo*, *Nelly* and *Acho*, *Ivan* and *Petia*, *Eva* and *Stoyan*, I am happy I have wonderful friends like you.

I would like to thank to my family – to my mother – *Margit* and my father - *Ognian*, to my brother – *Lyubomir* and my sister-in-law – *Borislava*. I really enjoyed your visits here, our family trips, our family dinners, our discussions and all the moments we spent together.

At last, I want to say THANK YOU *Ivaylo*. My dear love, I cannot express what you did for me all these years (already 10). Thank you for your support, thank you for taking care of me and for all the love you gave me. Thank you for being there for me when I had doubts about my work. Thank you for all the time we spent together and for the two lovely children we have – *Michail* and *Orlin*. Without them, my life would never be complete. I love you.

LIST OF ABBREVIATIONS

BMD	Bone Mineral Density
CMJ	Counter Movement Jump
COM	Center of Mass
CON	Control
CT	Computed Tomography
DS	Deep Squat
DXA	Dual X-ray Absorptiometry
EAV	Exposure Action Value
ELV	Exposure Limit Value
EMG	Electromyography
ES	Equilibrium Score
FAC	Functional Ambulation Classification
HS	High Squat
ISO norm	International Organization for Standardization
mPPT	Modified Physical Performance Test
RMS	Root Mean Square
RV	Rotational Vibrations
SOT	Sensory Organization Test
SWT	Shuttle Walk Test
TVR	Tonic Vibration Reflex
VV	Vertical Vibrations
WBV	Whole-Body Vibration

GENERAL INTRODUCTION

Vibration is a mechanical stimulus that appears to induce a reflex muscle contraction, and to affect neuromuscular performance. Nazarov and Spivak (1987) were the first to report that vibration stimulation could be an efficient method to improve muscle strength in athletes. Since then, many researchers have shown their interest in the effects of vibration training on muscle, bone and balance control.

Several studies showed that vibration training indeed may improve muscle performance, bone density or postural control in young adults, athletes and elderly, while others reported no changes in musculoskeletal performance. Therefore, the effects of vibration training are still controversial and the reason is the variety of vibration training protocols adapted by different investigators. The effects of vibration training on human body may depend, firstly, on vibration excitation patterns (frequency, amplitude and duration) and secondly, on the vibration exercise program (type of exercises, methods of vibration application, vibration intensity and volume).

Different investigators applied various vibration excitation patterns but not many research groups evaluated the transmission of vibration signal through the human body and the relationship between the applied vibration frequencies and amplitudes, and the induced muscle activation. The transmission of the vibration signal determines the extent to which different vibration parameters potentially contribute to positive or negative effects to human body. It remains important to evaluate not only the possible benefits of vibration on human body, but also the associated detrimental effects, especially on the head. Little is still known about the most optimal dose-response relationship between the vibration stimulus and its effect on muscle and bone. Therefore, further investigations are required to test the transmission of the vibration training stimulus from an efficacy and a safety perspective.

Except the transmission of vibration signal, the method of vibration application determines the way the vibration training affects the human body. While most studies documented the benefits of whole-body vibration on musculoskeletal performance, only very few studies applied vibration signals locally to the muscle belly or tendon. Additionally, effects of vibration training have mostly been assessed in athletes, healthy adults and elderly, while further research is still necessary to evaluate the possible beneficial effects of whole-body and local vibration training on muscle strength or bone density in other populations including neurological patients or frail elderly.

In general, the effects of vibration training on musculoskeletal performance and postural control remain controversial and therefore, general recommendations concerning the most beneficial vibration program can still not be provided. The most beneficial vibration training protocols for different populations including frail elderly and patients with neurological disorders remain unknown. The relationship between the optimal vibration exposure and its effect on musculoskeletal performance remains an important unanswered question. Therefore, the purpose of this doctoral project was to investigate different forms of vibration application – whole-body and local vibration, in an attempt to broaden the impact of vibration training to different populations. The doctoral project includes an overview of vibration training and the various vibration protocols employed by different investigators.

What is vibration and how does it work?

Vibration is a mechanical oscillatory motion characterized by its biomechanical parameters – frequency, displacement, acceleration and duration.[1] Frequency is defined as the number of vibratory cycles per unit time (Hz, s^{-1}). Amplitude is defined as the half of the displacement from the lowest to the highest point of the oscillatory motion (mm). The intensity of vibration load (vibration magnitude) is determined by the combination between vibration frequency and amplitude. It is defined as the maximum rate of change in velocity (m/s^2; g). Duration of one oscillation cycle determines the duration of vibration signal (s).

Vibration can be applied to the body either – 'directly' – when the vibration is applied directly to the muscle belly or tendon,[2,3] or 'indirectly' – when the signal is delivered by whole-body vibration platforms or transmitted through cables, dumbbells, and etc.[4-6]

Vibration applied directly to the muscle belly or tendon during vibration exercise provokes a phase-oriented discharge from both primary and secondary endings of the muscle spindles,[7] which depends on the pre-stretch of the muscles and increases with muscle length. Muscle spindle discharge elicits the alfa-motoneurons, resulting in a reflexive muscle contraction known as the tonic vibration reflex – TVR.[7] It is well-known that the TVR has both monosynaptic (Ia-primary afferents) and polysynaptic (II-secondary afferents) components and thus foster contractions of the homonymous muscle.[8] The TVR is continuously activated and the muscles contract and relax until the vibration stops.[9] Stretched muscles are more sensitive to vibration stimulation[10] and therefore, respond to vibration with a stronger contraction.[11] Other mechanisms have also been proposed to explain the effect of vibration stimulation on muscle response as for example an inhibition of the agonist-antagonist co-activation by means of Ia-inhibitory neurons and stimulation of central motor structures.[12] The magnitude of the TVR also depends on the applied vibration frequency.[12] The possible explanations for the higher EMG response during vibration compared to no-vibration are an increase in motor-unit synchronization and/or an increase in the sensitivity of the stretch reflex during vibration.[12]

During whole-body vibration the mechanism of muscle stimulation seems more complicated than the underlying mechanism of the tonic vibration reflex seen by direct vibration on the muscle tendon or belly. The vibration stimulus from the platform is attenuated by the body structures and the vibration signals that reach the target muscles are considerably reduced. The muscle response is stronger for the muscles that are closer to the vibration source due to the stronger stimulus.[13] In general, the indirect whole-body vibration stimulation may stimulate more muscle groups, whereas the effects of directly applied vibration are more localized.[14]

Vibration training and its efficacy perspective

Whole-body vibration (WBV) training is the most common and well-studied training approach. WBV is typically used to stimulate muscle strength and power of lower-limbs. During WBV training, a person stands on a whole-body vibration platform, while performing isometric or dynamic squats, and the vibration signal is delivered to the lower extremities. Until now, two different types of commercially available vibration training platforms are recognized. The first type (e.g. Power Plate®) produces vertical synchronous vibrations (VV – vertical vibrations) and the signal is transferred simultaneously (to both legs at the same time). The second type (e.g. Galileo®) produces side-alternating vibrations (RV – rotational vibrations) and delivers the signal asynchronous (first to one leg and then to the other one) which results in an asymmetric perturbation of the legs. It is still a matter of debate which type of platform induces higher muscle activation and results in better training effects. It is suggested that higher peak accelerations can better be tolerated when side-alternating vibrations are applied as a result of the rotational movements around the pelvis and lumbar spine, which diminish the transmission of the signal to the trunk.[15,16] However, it should be taken into account that RV devices often employ lower frequencies compared with VV devices that are considered as unsafe due to the possible body resonance.[17] Body resonance may occur when the applied vibration frequency reaches the natural resonance frequency of the human body (natural frequency is determined by the stiffness and mass of the human body). The resonant frequency could be harmful to the body.[18]

Several studies have tried to evaluate the WBV training stimulus from an efficacy perspective and therefore have demonstrated immediate effects on leg muscle activity during vibration stimulation.[11,19-22] Muscle activation during vibration may be measured recording the EMG signals of different target muscles. Most of vibration studies used surface electromyography to measure muscle activity during whole-body vibration. EMG signals can be used to verify if different vibration parameters (amplitude, frequency) will result in different muscular responses.

Roelants et al.[22] showed that vertical WBV exposure can induce an increase in muscular activity of rectus femoris, vastus medialis, vastus lateralis and gastrocnemius when frequency of 35 Hz and amplitude of 2.5 mm was applied. Greater muscle activation was found when a one-leg squat (125°) was performed compared with a high squat (125°) and a low squat (90°). In another study, the effects of two different commercially available platforms with the same vibration parameters – 30 Hz, 4 mm, were tested and the main outcomes showed that vertical vibrations led to significantly greater muscle responses of vastus lateralis and gastrocnemius whereas muscle activation of tibialis anterior was higher when rotational vibrations were applied.[19] Cardinale and Lim[11] studied three different frequencies – 30, 40, and 50 Hz and hypothesized that the different vibration frequencies would result in different neuromuscular responses. The findings of that study reported an increase in muscle activity of vastus lateralis compared with no-vibration in a group of professional women volleyball players who performed a half-squat position on the vibration platform (knee angle 100°). The highest muscle response of vastus lateralis was found when a frequency of 30 Hz was applied in comparison to 40 and 50 Hz.

In contrast to the previous studies, Pollock et al.[21] demonstrated that higher amplitude vibration and higher frequencies are associated with greater EMG responses compared to no-vibration. WBV training (RV platform) was performed at frequencies between 5 and 30 Hz at high (5.5 mm) and low (2.5 mm) amplitudes, and EMG signals of several lower-limb muscles were recorded. Likewise, Hazell et al.[20] reported a significantly greater muscle response of vastus lateralis, biceps femoris and tibialis anterior when frequency of 45 Hz was applied compared with 25 Hz and 35 Hz. WBV included 25, 35, and 45 Hz frequencies with 4-mm amplitude and a series of dynamic squats (unloaded with no WBV, unloaded with WBV, loaded with no WBV, and loaded with WBV) were performed.

Only a few studies have investigated the effect of WBV on upper limb muscles,[23-25] with controversial effects on upper body muscle performance.

In a study by Marin et al. [24] the participants held onto hand straps attached to a WBV platform at frequencies of 30 Hz (1.1 mm) and 46 Hz (2.5 mm). Although the reported results demonstrate that WBV exercise can increase muscle activity of biceps brachii in older adults, different frequencies and amplitudes did not result in different muscle responses.

Hazell et al.[23] found a significant frequency main effect, in which the 45 Hz frequency elicited significantly greater muscle activity of triceps brachii than all other frequencies (25, 30, 35, and 40 Hz) during static biceps curl. During dynamic biceps curl, a significant main amplitude effect was found, in which the 4 mm amplitude resulted in significantly greater muscle activity of biceps brachii and triceps brachii than did the 2 mm amplitude when collapsed across all frequencies. Although, some positive findings have been reported, the effects of WBV on muscle performance on upper-limbs are minor due to: 1) the attenuated vibration stimulus that reaches the upper limbs due to the distance between the vibration platform and the target muscles, 2) the attenuated transmission of the vibration from the feet to the arms, and 3) the damping properties of the human body.[23,26]

Therefore different tools such as vibrating dumbbells,[4] a muscle-tendon vibrator[27] or a vibratory stimulation device attached to a pulley system[28] have been tried to enhance transmission of the vibration stimulus to the upper body and improve upper body muscular performance. Bosco et al.[4] applied vibration at frequency of 30 Hz and displacement at 6 mm. They reported an increase around 100% in muscular activation of biceps brachii when a vibrating grip was used and dynamic elbow flexion was performed. Mischi&Bosco[29] used a vibrating actuator with frequency at 28 Hz and the amplitude of the input sinusoidal waveform was set to 1.2 V. Increases in muscle activity of biceps brachii and triceps brachii were found while isometric arm extension and flexion tasks were performed. Silva and co-workers[30] used locally applied vibration at 8 Hz, 6 mm in a direction opposite of muscle shortening (vibration applied not perpendicularly to the tendon or muscle). An increase in maximal voluntary contraction (MVC) of elbow flexion was found in untrained male adults. Moran et al.[27] showed no effect of vibration stimulation (65 Hz, 1.2 mm) on muscle activity in maximal effort (70% 1RM) dynamic biceps curls when vibration was delivered by a portable muscle-tendon vibrator attached over the biceps tendon. The authors suggested that different mechanisms for neuromuscular enhancement from vibration training might be employed during submaximal isometric and maximal-effort dynamic exercises, requiring different magnitudes of amplitude and frequency of vibration then the one applied in their study.

In general, the presented vibration studies applied different vibration frequencies and amplitudes, and therefore it is difficult to assess which vibration parameters would result in better neuromuscular responses. It is still unknown which vibration parameters would elicit the most beneficial muscle activation, especially when some studies reported that frequency of 30 Hz are recommended to induce a higher muscle response while others reported a significant frequency main effect, in which the 45 Hz frequency elicited significantly greater muscle activity than frequencies from 25 to 40 Hz.

It should be underlined that different EMG data analysis may contribute to the heterogeneous findings. In several studies only notch[19,21] or band-pass filters[22] were applied to analyze the EMG activity during vibration exercises. Using only band-pass filters might result in an overestimation of the real muscle response caused by motion artifacts due to the vibration.[19,31] These motion artifacts are associated not only with the applied vibration frequency but also with the vibration of the cables and electrodes. However, the application only of notch filters might cause an underestimation of the true magnitude of the muscular response by eliminating real vibration induced motor-unit firings at the vibration filtered frequency.[32] Notch filters are typically set at the frequency of the vibration source. The ‘true’ muscle response due to WBV lies in between the two approaches.

Literature overview

1. Whole-body vibration

    a. Musculoskeletal performance

The most optimal muscle loading has widely been studied among young and healthy populations,[5,33,34] athletes[35-37] and elderly.[38-42] To assess the effects of acute, short- and long-term vibration therapy, a wide range of vibration parameters have been adapted by different research groups.

Acute vibration exposure appears to be a useful modality when applied during pre-competition warm-up especially among trained adults and athletes. Following acute 30-second bouts at frequencies of 30, 35 and 40 Hz, vertical WBV resulted in a significant improvement in counter movement jump (CMJ) height in a group of trained men only at a frequency of 40 Hz.[43] In a study by Cormie et al.[44] healthy young men underwent 30 seconds of vertical WBV at frequency of 30 Hz and amplitude of 2.5 mm. An increase in CMJ was reported immediately after the vibration but not 5, 15 or 30 minutes after the intervention. Other research group studied different vibration frequencies – 30 Hz (2.18 *g*), 35 Hz (4.87 *g*), 40 Hz (2.80 *g*), and 50 Hz (5.83 *g*) which did not change CMJ height in a group of young male and female adults following acute 45-second bouts of vertical vibration.[45] Different vibration parameters were also tested by Siu et al.[46] – 26 Hz/4 mm and 40 Hz/1.69 mm. Ten bouts of 60 seconds WBV training (RV) resulted in a significant improvement in concentric and eccentric peak torque of knee extensor and flexor muscles in a group of active male adults; however, no difference in effect was found between the two frequencies. Similar vibration parameters were studied in a study by Stewart et al.[47] – 26 Hz, 4 mm, RV where isometric knee extension strength increased significantly after 2 minutes of WBV in trained male participants. However, in the same study, 4 and 6 minutes of vibration intervention led to knee extension strength decreases explained with muscle fatigue induced by vibration. Torvinen et al.[13] also reported an improvement in isometric muscle strength and jump height among young adults after a single bout of 4 minutes of vibration (15 – 30 Hz, 3.5 – 14 *g*, RV) that resulted in muscle fatigue.

Regarding the application of show- and long-term vibration training, several studies evaluated the effects on musculoskeletal performance in different populations (Table 1 and 2).

Study	Frequency (Hz)	Amplitude (mm) acceleration (*g*)	Platform	Duration	Population	Outcomes
Delecluse, 2005[35]	35 – 40	1.7 – 2.5 mm	VV	5 weeks (3x/wk)	sprint-trained athletes, 17–30 y	no changes in isometric and dynamic knee strength
Delecluse, 2003[5]	35 – 40	2.5 – 5 mm	VV	12 weeks (3x/wk)	sedentary female, 21.4±1.8 y	an increase of isometric and isokinetic muscle strength, CMJ height
De Ruiter, 2003[48]	30	8 mm	RV	11 weeks (3x/wk)	healthy subjects, 19.9±0.6 y	no changes in isometric knee extension strength, maximal rate of voluntary force rise and CMJ height
Fagnati, 2006[36]	35	4 mm	VV	8 weeks (3x/wk)	female athletes, 21–27 y	an improvement in isokinetic leg press and CMJ height
Humpries, 2009[49]	50	NR	RV	16 weeks (3x/wk)	healthy active women, 21.02 y	no significant group differences in BMD
Kvorning, 2006[50]	20 – 25	4 mm	RV	9 weeks (3x/wk)	healthy men, 23±0.7 y	no changes in maximal isometric voluntary contraction and CMJ height
Lam, 2012[51]	32 – 37	0.3 *g*	NR	12 months (5x/wk)	adolescent idiopathic scoliosis girls, 15–25 y	an increase in aBMD at the femoral neck of the dominant side and lumbar spine
Roelants, 2004[33]	35 – 40	2.5 – 5 mm	VV	6 months (3x/wk)	untrained females 21.3±2.0 y	an increase in isometric and dynamic knee muscle strength
Torvinen, 2002[34]; 2003[52]	25 – 45	2 – 8 *g*	RV	4- and 8 months (3-5x/wk)	adults, 19–38 y	an improvement vertical jump height no changes in BMD of the femoral neck or lumbar spine

Table 1. Characteristics of whole-body vibration training in young adults. NOTE: BMD – bone mineral density; CMJ – counter movement jump; NR – not reported; RV – rotational vibrations VV – vertical vibrations.

Study	Frequency (Hz)	Amplitude (mm) acceleration (*g*)	Platform	Duration	Population	Outcomes
Bautmans, 2005[53]	30 – 50	2 – 5 mm	VV	6 weeks (3x/wk)	nursing home residents, 77.5 y	no changes in isokinetic leg extension
Bemben, 2010[54]	30 – 40	2 – 2.8 *g*	VV	8 months (3x/week)	estrogen-deficient PMW 55–75 y	a decrease in right total hip and right femoral neck
Bogaerts, 2007[38]	35 – 40	2.5 – 5 mm	VV	1 year (3x/wk)	community-dwelling men 67.3 y	an increase in jump performance, isometric knee extension strength, and in thigh muscle mass
Gusi, 2006[55]	12.6	3.3 *g* – lateral, 0.7 *g* – vertical	RV	8 months (3x/wk)	PMW, 66 y	a net benefit of 4.3% BMD at the femoral neck
Iwamoto, 2005[56]	20	0.70 – 4.2 mm	RV	12 months (1x/wk)	PMW, 70.6 y + alendronate	reducing chronic back pain
Machado, 2010[57]	20 – 40	2 – 4 mm	VV	10 weeks (3-5x/wk)	postmenopausal women, 79 y	no changes in isotonic muscle strength an increase in isometric muscle strength and in thigh muscle cross-sectional area
Rees, 2008 [40]	26	5-8 mm	RV	8 weeks (3x/wk)	nursing home residents, 73.7 y	no changes in knee muscle strength
Roelants, 2004[41]	35 – 40	2.5 – 5 mm	VV	6 months (3x/wk)	PMW, 58–74 y	an increase in CMJ, isometric and isokinetic muscle strength
Russo, 2003[58]	12 – 28	NR	RV	6 months (2x/wk)	PMW, 60.7 y	an increase in muscle power no changes in bone characteristics.
Slatkovska, 2011[59]	30 and 90	0.3 *g*	NR	12 months	PMW, 60.5 y	no effect on any bone outcomes
Trans, 2009[60]	30 – 35	NR	VV	8 weeks (2x/wk)	female patients, 60.4 y diagnosed with knee osteoarthritis	an increase in isometric knee-extension strength
Verschueren, 2004[42]	20 – 40	2 – 4 mm	VV	6 months (3x/wk)	PMW, 58–74 y	a net benefit of 1.5% BMD at the hip
Verschueren, 2011[61]	30 – 40	1.6 – 2.2 *g*	VV	6 months (3x/wk)	PMW, 70 y + vitamin D	no muscle hypertrophy of the lower limb an increase in BMD of the hip compared with baseline
Von Stengel, 2012[62,63]	25 – 35	1.7 – 2 mm	NR	18 months (2x/wk)	PMW, 68.5 y	no additive effects on isometric extension muscle strength and CMJ an increase in BMD at the lumbar spine

Table 2. Characteristics of whole-body vibration training in elderly. NOTE: BMD – bone mineral density; CMJ – counter movement jump; NR – not reported; PMW – postmenopausal women; RV – rotational vibrations; VV – vertical vibrations.

It is noticeable that the reported vibration studies included different vibration platform devices that delivered either vertical or rotational vibrations. Vibration parameters also differed among the studies. While the vibration frequencies of the vertical vibrations ranged between 20 and 50 Hz and the amplitudes ranged between 1.7 and 5 mm, frequencies of rotational vibrations ranged from 12.6 to 50 Hz and amplitudes – from 0.7 to 8 mm. Only one study compared two different vibration frequencies – 30 and 90 Hz in one population; however, no positive effects on BMD were reported independently of the applied frequency.[59] Not only did the vibration parameters vary between each other, but the number of sessions per day (between 3 and 6 in the different studies) and the duration of one session (between 20 and 80 seconds) contributed to the controversial findings. Differences in training protocols can also be found with respect to study durations – from few weeks to 1 year. These heterogeneous vibration protocols contribute to the inconsistency of the study outcomes. Therefore, future studies need to be conducted to determine the optimal vibration protocols to maximize neuromuscular performance in short- and long-term vibration settings.

b. Postural control and risk of falls

As mentioned already a relevant number of WBV studies have examined the effects of vibration training on various aspects of lower-limb muscle strength among different populations.[38,42,57] Neuromuscular performance is highly related to body balance and mobility function,[64] and this, together with the evidence that vibration can improve proprioceptive function,[65] could explain why vibration exercises might also benefit balance and risks of falls. WBV training appears to improve specific aspects of postural control in older individuals including postmenopausal women or community dwelling adults.[42,53,66] Postural control was assessed via different balance tests for dynamic balance (Timed-up-to-go test, Sensory Organization Test, Tandem walk test chair rising),[53,66-69] static balance (Balance Master System, Balance index, Posturography on force plates)[68,70,71] and for functional balance (Tinetti test).[53,69] However, findings have again been inconsistent, with no effect of WBV on dynamic and static postural control in several studies.[6,52,67,72] The possible reasons for the inconsistent findings could be found in the vibration protocols used in the different studies. The applied frequency varied between 12 and 40 Hz for vertical vibrations and between 5 and 26 Hz for side-alternating vibrations. The applied amplitude ranged between 0.5 mm to 8 mm in both types of vibration. The duration of vibration exposure ranged between 30 and 60 seconds per bouts and the number of bouts – between 3 and 10 per session. Vibration groups trained between 1 and 3 times a week for a period of 6 to 52 weeks. In terms of exercises, the participants were asked to perform either only static and dynamic exercises or a combination of both. In general, firm and clear conclusions concerning the most beneficial protocol cannot be made due to the variety of vibration parameters (frequency, amplitude, duration) used in the different studies.

c. Neurological disorders – chronic stroke patients

The literature overview above showed that WBV intervention has increasingly been promoted to improve neuromuscular performance among young and healthy populations,[5,33-36] athletes,[36,37] and elderly.[38-42] Some studies also suggested the potential beneficial effects of vibration training in patients with different neurological chronic conditions.[73] To date, chronic stroke remains the leading cause of adult disability[74] with motor deficits and physical impairments including muscle weakness, loss of mobility, muscle spasticity and balance problems.[75] These impairments may promote a sedentary lifestyle and contribute to secondary complications like bone loss and fracture risk.[76] Muscle weakness results in low muscle forces and thus, a deficit of motor control and movement initiations.[77] Balance problems increase the risk of falls in adults with stroke.[78] Most of the training programs for patients with chronic stroke have only addressed one (or two) of the impaired domains, e.g. either strength or balance. Therefore, WBV training might be a useful multidimensional approach to counter several of the impairments of the adults with chronic stroke. However, only a few studies have evaluated the long-term[79-81] and immediate [82,83] effects of vibration training on patients with chronic stroke.

After one session of WBV (RV) at frequency of 20 Hz and amplitude of 5 mm, an increase in isometric knee extension strength was reported in patients with post-acute stroke compared with baseline; however, no between-group differences were reported.[82] In one randomized controlled pilot study, vertical vibration was set at frequency of 25 Hz and amplitude of 3.75 mm. [79] The participants performed only static knee squats twice a week for 6 weeks. The vibration lasted 40 to 60 seconds, with maximum 12 repetitions per session. No significant improvements in muscle strength, gait performance or muscle spasticity were reported compared with baseline and compared with a control group. In another study which also lasted 6 weeks (5/weekly, less than 4 minutes vibration), no effects were found on functional tests like the Berg Balance Scale or the Barthel Index. Vibration frequency was set up at 30 Hz and vibration amplitude was 3 mm.[81] In a longer study by Lau et al.[80] a vibration intervention of 8 weeks had no additional effect on neuromotor performance and incidence of falls in adults with chronic stroke compared to controls that performed the same exercises but with no vibration. However, in that study vibration therapy was less intensive – 3x/week, 20 – 30 Hz, 0.44 – 0.6 mm.

In conclusion, the most beneficial vibration training parameters for adults with chronic stroke remain unknown. Positive effects of a more intensive vibration therapy on this specific population of neurological patients cannot be excluded**.**

2. Local vibration training

So far, many studies reported the beneficial effects of WBV on muscle performance whereas only very few research groups studied the possible beneficial effects of locally applied vibrations on muscle performance.[84,85] Pietrangelo et al.[84] studied the effects of locally applied vibrations on the thigh muscles in male and female elderly diagnosed with sarcopenia. Vibration application at frequency of 300 Hz lasted 12 weeks/1-3x/wk for 15 minutes. The researchers showed an improvement in isometric muscle strength, which was higher in the female than in the male participants. Brunetti et al.[85] have shown that vibration of 3 applications (of 10 min) every day over 3 consecutive days on the quadriceps enhances the single-limb stability in young male patients with anterior cruciate ligament (ACL) reconstruction (100 Hz, < 20 μm). Balance control was assessed using the center of pressure from a force plate and the center of pressure averaged speed (mm/s) was estimated.

Therefore, more research is needed to test the possible benefits of locally applied vibrations in different populations. Application of local vibration training might be more effective at the regions at the most in need of muscle strengthening.

Vibration training and its safety perspective

It is clear that vibration training load is dependent on vibration parameters – amplitude, frequency, duration and acceleration. Changes in vibration frequency and amplitude determine the changes in vibration acceleration transmitted to the human body. Vibration transmission depends also on the damping properties of the muscles, tissues and fluids, as well body posture, especially the knee joint angle. The transmission of the vibration signal up to the head can in this respect be diminished by knee flexed position.[19] According to Rittweger,[32] an appropriate body posture might alter significantly the transmission of the signal to the trunk by posing more weight on the forefoot and therefore, to increase the damping properties of the muscles.

Vibration transmission plays a crucial role in neuromuscular and bone stimulation of the body; however only very few research groups have studied the transmission of the vibration stimuli to the human body used for muscle and bone simulation (Table 3).[21,86-89]

The available studies did not evaluate variety of key points: either the vibration transmission was measured only up to the lower spine,[87-89] or the participants performed only light squat or erect stance position,[87,89] or only uni-axial accelerometers were used to measure the propagation of the vibration signal.[86] Only in the study of Pollock et al.[21] the transmission of the vibration signal was measured from the platform up to the head and additionally, the dose-response relationship between different vibration excitation patterns and induced muscular activation was evaluated. However, only erect stance position was performed and the investigated frequencies ranged between 5 and 30 Hz, which are not commonly used in WBV studies.

In general, the vibration transmission attenuates when propagating through the body but higher peak accelerations have been reported at some body points compared to the peak accelerations delivered by the vibration platform, which could result in overloading of the body. None of the reported studies evaluated the safety aspect of whole body training while follows the basic evaluation method from ISO2631 (1997).[90] This is partly due to the fact that norm ISO2631 is mostly based on research with vertical vibration of seated persons and occupational vibration exposure,[90] with no norm developed specifically for standing persons. Nevertheless, the safety aspect of WBV training seems crucial for evaluation of WBV training regimes.

Study	Frequency (Hz)	Amplitude (mm) Acceleration (*g*)	Platform	Population	Studied body points	Knee angle	Method of measurement	Main outcomes
Harazin, 1998[86]	4 – 250	0.4 *g*	NR	10 male students 23.1 y	ankle, knee, hip, shoulder, head	10 different postures	accelerometers	Decrease of the transmission with an increase of the frequency
Kiiski, 2008[87]	10 – 90	from 0.05 to 3 mm	VV	4 clinically healthy men	ankle, knee, hip, L3	erect stance	accelerometers	Amplification at the ankle, knee, hip, and spine.
Pel, 2009[88]	25	PowerPlate 3 *g* Galileo 4.8 *g* PowerMaxx 0.14 *g*	PowerPlate, VV Galileo, RV PowerMaxx	8 healthy, 34 y	ankle, knee, hip	100° knee angle	accelerometers	Amplification at the ankle
Pollock, 2010[21]	5 – 30	2.5 and 5.5 mm	RV	15 healthy, 36 y	toe, ankle, knee, hip, head	15.1 (4.8)° knee flexion	3D motion analysis	Acceleration at the head was always 0.33 g. The greatest acceleration of the knee and hip occurred at ~15 Hz
Rubin, 2003[89]	15 – 35	up to 1 *g*	NR	5 healthy adults	hip, L4	erect stance and 20° knee flexion	accelerometers	Erect stance: amplification at the hip for frequencies < 20 Hz; frequencies 25 Hz, transmissibility decreased at the hip and spine. 20 ° knee flexion reduced transmissibility.

Table 3. Characteristics of whole-body vibration studies which reported vibration transmission. NOTE: L3 – lumbar spine; NR – not reported; RV – rotational vibrations; VV – vertical vibrations.

Conclusion and remaining questions

In summary, the studies in the literature provide some evidence of the effectiveness of vibration training as a training method in sports, rehabilitation and medical prevention. Short- and long-term vibration exposure has been shown to improve different aspects of muscle strength and power, bone mineral density and postural control in different populations. However, currently, the effects of vibration on muscle, bone and body balance are still unclear and controversial due to the variety of vibration protocols used in the different studies. The vibration protocols can vary in the vibration loading parameters (frequency, acceleration, and duration), the type of the applied vibration, the duration of the vibration exposure, the exercises performed during the training, etc.

Vibration effects on musculoskeletal performance depend on the vibration transmission and the mechanism by which the propagation of the signal is altered either by the biomechanical properties of the human body or the applied vibration excitation patterns. However, little is known about the extent to which variations in the vibration excitation signal (frequency, amplitude) alter the transmission of the stimulus from the vibration platform to the upper body and potentially contribute to beneficial or detrimental effects to the bone and to the lower- and upper-limb muscle groups. The use of WBV therapy for therapeutic purposes is still not standardized. **As a result, it remains uncertain how to evaluate the WBV training stimulus, both from an efficacy and from a safety perspective.**

Therefore, two main key points need still to be addressed **(Chapter 1 and 2)**:

(1) How to evaluate the WBV training stimulus from an efficacy perspective – what is the dose-response relationship between different vibration excitation patterns (acceleration, frequency) and the induced muscular activation with respect to different body postures and exercises?

(2) How to evaluate the WBV training stimulus from a safety perspective – what are the exposure limit values and how is the transmission of the vibration signal altered through the entire body up to the head over a wide range of vibration excitation patterns?

Although, it is considered that WBV training might be a useful multidimensional approach to counter several of the impairments (incl. muscle weakness, motor dysfunction, and balance problems) of adults with chronic stroke, the presented literature overview did not completely support the concept of vibration as a potential therapy for these patients. The results from the different studies remain controversial, which could be explained with the too low intensity of the vibration training program (very short duration) and/or that vibration excitation patterns could not produce a therapeutic effect in patients with stroke. Additionally, the exercises performed on the platform might not have been challenging enough (only static exercises). **In this context, the most beneficial vibration training protocol for this specific population of patients still remains unidentified.** Therefore, positive effects of a more intensive WBV training on adults with chronic stroke cannot be excluded **(Chapter 3).**

Whole-body vibration has been widely studied among older adults who are at high risk for osteoporosis and sarcopenia, thus, at high risk for falls and fractures. **However, whole-body vibration therapy in its present form (subjects standing on a vibrating platform) might be an inappropriate training method for a large segment of the elderly population including patients with prosthesis or bedridden individuals.** Delivering the vibration stimulus locally at the regions with the highest risk for fractures (trochanter major and lumbar spine) or most in need of muscle strengthening might be more effective **(Chapter 4).**

AIM OF THE PROJECT

The specific objectives of the doctoral research project are:

- To evaluate the transmission of whole-body vibration through the entire body up to the head over a wide range of accelerations and frequencies and its relationship with the induced muscle activation.

- To evaluate the transmission of whole-body vibration through cables to the upper body and its relationship with the induced muscle activation.

- To assess the feasibility, safety and possible beneficial effects of an intensive whole-body vibration program in patients with chronic stroke.

- To assess the feasibility, safety and possible beneficial effects of locally applied vibration therapy in postmenopausal women.

These objectives were realized through four different studies, which are outlined in the section below.

OUTLINE

Chapter 1 aims to explore the transmission of whole-body vibration through the entire body up to the head over a wide range of accelerations and frequencies with relation to muscular activation and body posture. This study will allow identifying the extent to which variations in the vibration excitation signal (frequency, amplitude) alter the transmission of the stimulus from the vibration platform to the upper body and potentially contribute to beneficial or detrimental effects to muscle and bone.

In **Chapter 2**, a new vibration device with cable-pulley resistance system attached to a vibration platform was tested in an attempt to channel the vibration indirectly from the platform to the upper body and potentially broaden the impact of training to the whole body. Vibration transmission through the cables to the upper body was evaluated and a dose-response relationship between vibration parameters and induced muscle activation was identified.

The study in **Chapter 3** was designed as a randomized controlled pilot trial for patients with chronic stroke in an attempt to broaden WBV training to different populations than young adults and healthy elderly. Potential effects on knee muscular strength and muscle spasticity were assessed after 6 weeks of intensive whole-body vibration training. The effects on static and dynamic balance as well as clinical measures of functional performance (standard clinical neurological examination, Barthel Index, functional ambulation classification, Brunström-Fugl-Meyer test) were assessed.

In **Chapter 4**, a different form of vibration training – local vibration training, was applied in an attempt to broaden the impact of vibration intervention to frail elderly. First, based on a finite element model of a femur constructed to compare local loading to the loading as induced by standing on a platform, custom-made vibration devices were specially designed for the this doctoral project. Second, we conducted a pilot randomized controlled trial for postmenopausal women who underwent 6 months of locally applied vibrations at the mid-thigh and around the hip. Effects on static and dynamic knee muscle strength, muscle mass, and bone mineral density were assessed. Additionally, a modified physical performance test and a shuttle walk test were performed to study the effects of vibration training on physical performance.

The doctoral project will be concluded by a **general discussion**, in which the main outcomes are summarized and discussed, and recommendations for future research are proposed.

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CHAPTER 1

Transmission of whole-body vibration and its effect on muscle activation

J Strength Cond Res 27(9): 2533–2541, 2013

Ekaterina Tankisheva [1]
Ilse Jonkers [2]
Steven Boonen† [3]
Christophe Delecluse [4]
G. Harry van Lenthe [5, 6]
Hans Druyts [5]
Pieter Spaepen [7]
Sabine M.P. Verschueren [1]

[1] KU Leuven – University of Leuven, Department of Rehabilitation Science, Musculoskeletal Rehabilitation Research Centre
[2] KU Leuven – University of Leuven, Department of Biomedical Kinesiology, Research Centre for Movement Control and Neuroplasticity
[3] KU Leuven – University of Leuven, UZ Leuven, Department of Experimental Medicine
[4] KU Leuven – University of Leuven, Department of Biomedical Kinesiology, Research Centre for Exercise and Health
[5] KU Leuven – University of Leuven, Department of Mechanical Engineering, Biomechanics Section
[6] Institute for Biomechanics, ETH Zurich, Zurich, Switzerland
[7] Katholieke Hogeschool Kempen, Geel, Belgium

ABSTRACT

The aim of current study was to measure the transmission of whole-body vibration through the entire body and to relate this to body posture and induced muscular activation.

Eight clinically healthy subjects performed 3 static body postures – high squat (135°), deep squat (110°) and erect stance, while vibration transmission was assessed over a wide range of accelerations (from 0.33 to 7.98 *g*) and frequencies (30 to 50 Hz). To assess the vibration transmission, nine tri-axial accelerometers were attached from the ankle up to the head and the root-mean-square (RMS) of acceleration signal of each site-specific body point was calculated. Additionally, muscle activity from 7 lower limb muscles was recorded. The results showed a significant attenuation of the platform accelerations transmitted from the feet to the head. Compared to erect stance, knee bent posture significantly diminished vibration transmission at the hip, spine and the head ($P<0.05$). Vibration transmission to the spine was significantly lower in deep versus high squat ($P<0.05$), suggesting that further knee bending may reduce the risk of overloading the spine. Vibration increased the muscle activity in most leg and hip muscles during both squat postures, although, on average, no clear dose-response relationship between the acceleration and/or frequency and muscle response was found. The muscular activation of vastus medialis and rectus femoris showed clear negative correlation to the vibration transmission at the sternum.

The specific vibration parameters used in the present study can be considered as safe and suitable for a training program. Moreover, the present results contribute to optimize the most advantageous whole-body vibration protocol and to determine the beneficial effects on muscle and bone.

Key words: acceleration, mechanical loading; neuromuscular stimulation; body posture; safety.

INTRODUCTION

Recently, whole-body vibration (WBV) training has been suggested to increase muscle mass and strength, improve bone quality and postural balance.[1-3] During WBV training, a person stands on a platform that generates vertical sinusoidal vibrations. The oscillation transmission provokes an activation of muscles. These are commonly explained by excitation of the muscle spindles resulting in an activation of the alpha-motoneurons, followed by muscle contraction comparable to the tonic vibration reflex.[4] Other mechanisms have also been proposed as for example an inhibition of the agonist-antagonist co-activation by means of Ia-inhibitory neurons.[5]

Effects of WBV training on muscle strength, postural balance and bone density have been extensively studied but the results remain inconclusive and often inconsistent. Several WBV studies have shown an increase in muscle strength,[2,3,6] bone density[3,7] and specific aspects of postural control[3] in different populations due to WBV training. However, other research groups have found no positive effects of WBV on muscle strength,[8,9] or bone and body balance.[10] This inconsistency of the effects of WBV training may be related to the different vibration training parameters and protocols used in different studies, more specific: the frequency and the magnitude of the vibration signal, the type of vibration signal, the type of vibration platform, the number and type of exercises, the duration of the vibration intervention, and the period of the study. The use of different vibration signal parameters is likely to affect the acceleration transmitted to different body parts and consequently the bone and muscle loading. Several studies have assessed the transmission of vibration to the body during vertical stimulation over a different range of vibration frequencies and magnitudes.[11-15] In general, the vibration transmission attenuates when propagating through the body but higher peak accelerations have been reported at some body points compared to the peak accelerations delivered by the vibration platform, which could result in overloading of the body.[12,14] Little is still known about the extent to which variations in the vibration excitation signal (frequency, amplitude) alter the transmission of the stimulus from the vibration platform to the upper body and potentially contribute to beneficial or detrimental effects to muscle and bone. As a result, it remains uncertain how to optimize the WBV training stimulus, both from an efficacy and from a safety perspective. Thus, the aim of the current study was to evaluate the transmission of whole-body vibration through the entire body up to the head over a wide range of accelerations and frequencies with relation to muscular activation and body posture.

METHODS

Experimental Approach to the Problem

To evaluate the transmission of whole-body vibration, the accelerations of several body points were measured at a range of vibration frequencies (30 to 50 Hz) and accelerations (from 0.33 to 7.98 *g*) delivered by vibration platform in 3 different body postures: erect stance, high squat and deep squat. To measure the muscular activation during vibration training, the EMG of different muscle groups was recorded. Additionally, to quantify the effect of body posture on vibration transmission we studied 3D inverse kinematics and specifically, the center of mass during the vibration training.

Subjects

Eight clinically healthy volunteers (5 males and 3 females: age = 28.7 ± 6.42 years; height = 1.76 ± 0.09 m; body mass (kg) = 65.8 ± 8.33 kg) participated in the study. Subjects were free from conditions that would not allow whole-body vibration training – neurological or musculoskeletal disorders, acute inflammations, cardiovascular and pulmonary diseases, pregnancy or any chronic disorders. None of the participants had previously participated in any studies of whole-body vibration. All subjects were informed about the purpose of the study, and about the possible risks and benefits of the training. They all gave written consent to participate. This study was approved by the Leuven University’s Human Ethics Committee according to the declaration of Helsinki.

Vibration platform

Three commercially available vibration platforms inducing vertical sinusoidal vibration were used for the present study (Powerplate, Badhoevedorp, The Netherlands). Each platform was set at 30, 35, 40 and 50 Hz, and low and high acceleration modes. The vibration signal was delivered at the same time to the both legs. Each platform consists of two electro motors provided with an eccentric mass that controls the vibrations. To be able to induce vertical vibrations to the body over a wide range of accelerations, two of the platforms were adapted by changing their eccentric mass. As a result of platforms’ adjustment, the vibrations delivered by the three platforms ended in a wide range of vertical peak accelerations.

Vibration protocol

Each subject participated in a single data – collection session. They were encouraged to report immediately any unusual symptoms (e.g., discomfort, queasiness) during WBV. Participants were barefoot and were instructed to stand in the centre of the platform and held onto the handles. They maintained one of three postures: standing upright with knees fully extended (erect stance), knees flexed at 135° (high squat – HS) and at 110° (deep squat – DS), where the fully extended position was described as 180°.[16]

The protocol was organized in 6 consecutive series – one series for low acceleration mode and one series for high acceleration mode for each of the three platforms. Each series included 8 trials – 2 positions x 4 frequencies (30, 35, 40 and 50 Hz). Additionally, for safety, the erect stance was performed only at two combinations of frequencies and accelerations – 35 Hz/ 0.40 *g*, and at 40 Hz/ 0.50 *g*, because the extended knee position increases the transmission to the upper body. Those parameters have been demonstrated to be safe in this position.[12]

Each trial lasted 40 seconds consisting of 10 seconds without and only 30 seconds with vibration. A rest of five minutes was provided after two consecutive series. The protocol was based on daily vibration exposure limits indicated in ISO norm 2631-1[17] and adapted from Kiiski et al. (2008).[12] To avoid bias of the results due to fatigue, the order of the six series was randomized between subjects. A rest of five minutes was provided after two consecutive series.

Specific equipment

To measure the transmission of the vertical vibration from the platform to specific body points, 9 tri-axial accelerometers (micro-electro-mechanical system, SMB380, Bosch Sensortec Gmbh, Reutlingen, Germany) mounted on custom made printed circuit board and with custom data acquisition board (Zenso NV, Heverlee, Belgium) were used. The mass of each accelerometer was 0.6 g and the size 12 mm x 14 mm x 2.5 mm (WxLxH). The calibration of the SMB accelerometers was checked against a standard piezo-accelerometer, revealing a linear relationship up to a magnitude of 7 *g*. The accelerations in the study refer to total accelerations, which were calculated as the root of the sum of the squared components, and can therefore exceed 7 *g*. All accelerations were sampled at 1 kHz. The accelerometers were attached with adhesive tape to the subject’s skin at overlying specific body points: head (H), manubrium of the sternum (S), vertebra prominens – C7 (VP), third lumbar vertebra

(L3), anterior superior iliac spine (SISA), greater trochanter (TM), medial condyle of the femur (MC), tuberositas tibiae (TT) and medial malleolus (MM), respectively. All electrodes and cables were secured by bandages to prevent swinging and consequent movement-induced artifacts. Additionally, one accelerometer was attached to the platform to provide accurate data on the different platform accelerations. Vibration signals were analyzed both in time and frequency domain using Matlab. Raw signals were filtered using a high pass 8^{th} order butterworth filter (10Hz) with a zero-phase forward and reverse filtering (zero phase distortion). The frequency was determined by analyzing the acceleration time signal using discrete fourier transformation, and more specific the single sided amplitude spectrum. In the time domain, the signals were analyzed by computing both the root-mean-square (RMS) of acceleration and the peak-to-peak acceleration values at the different body points. The first and last quarter data section of the time signal was not used for data analysis to avoid lead-in and lead-out phenomena. The transmission of the acceleration was determined as a ratio of RMS of a site-specific body point to the RMS of the vibration platform.[12]

To evaluate the safety aspect of whole-body training, we followed the basic evaluation method from ISO2631 (1997).[17] According to this norm, the weighted root-mean-square (r.m.s.) acceleration is calculated as:

$$a_{eq} = \sqrt{\frac{1}{T}\int a_w^2(t)dt}$$

where $\mathbf{a_w(t)}$ is the weighted acceleration as a function of time in m/s^2, measured at the interface between the human body and the source of its vibration, in this case the vibration platform, and $\mathbf{T}$ is the duration of the measurement in seconds. As the weighting functions for the evaluation of vibration on health effects in standing persons are not specified in norm 2631 (1997), we used the weighting function w_k, similar to the use of the weighting function w_b in norm BS6841 and to the use of the weighting function w_g in norm 2631 (1974). The European vibration directive 2002/44/EC [18] established to protect users of load vehicles from the effect of vibration, stipulates the calculation of an 8-hour energy-equivalent frequency-weighted acceleration (known as the A(8) value). The vibration exposure is evaluated by comparing the A(8) value to a daily Exposure Action Value (EAV, 0.5 m/s^2) and a daily Exposure Limit Value (ELV, 1.15 m/s^2). The time to reach the EAV or the ELV during a whole-body training session was calculated from A(8) value and the weighted root-mean-square acceleration – Aeq.

To measure the muscular activation during vibration training, a total of seven wireless bipolar surface EMG electrodes (ZeroWire, Aurion, Italy) recorded the EMG signals from: soleus, tibialis anterior, vastus medialis, rectus femoris, medial hamstrings, and gluteus maximus and medius, respectively. The skin was shaved and cleaned with alcohol. The EMG electrodes were mounted to the body according to the SENIAM protocol[19] and additionally fixed to the muscle using adhesive tape to guarantee their position and contact during WBV. To avoid crosstalk caused by EMG signals coming from neighboring muscles, the electrodes were placed at the middle of the muscle belly and an appropriate inter-electrode (center-to-center) distance of 20 mm was chosen. EMG-signal validity was checked visually before starting the EMG-recording.[19] The EMG signals were amplified and sampled at 1000 Hz. The EMG was visually checked and further analyzed using two different approaches: in the first approach a band-pass filter between 10 and 500 Hz was applied; in the second approach, additionally, a band-stop filter (notch) was applied. The notch filter was implemented to eliminate possible artifacts at the exact excitation frequency of the platform working at 30, 35, 40 and 50 Hz, respectively. An average root-mean-square (RMS) was calculated for non-vibration and vibration periods.

A Krypton 3D system (Nikon Metrology NV, Leuven, Belgium) was used to measure the body kinematics during WBV. The system consists of 2 x 3 linear CCD cameras detecting infrared light emitted by LEDs. Five technical clusters, each consisting of three markers, were positioned on the head, the upper trunk, the sacrum, the left thigh, and the left shank, respectively. Four markers were attached to bony landmarks of the left leg: epicondylus lateralis femoris, malleolus lateralis, os calcaneus, and between os metatarsale 1 and 2, respectively. Three markers were placed on the platform. The relation between the clusters and the anatomical landmarks was defined during an anatomical calibration procedure in which the position of selective anatomical points (medial and lateral malleolus, medial and lateral femoral epicondyle, right and left SISAs, incisura jugularis, and right and left acromion, respectively) was registered to the cluster position using a measurement probe. To ensure correct positioning of the subjects during the trials, real-time visual feedback was provided by superimposing video captured position of shoulder, hip, knee and ankle markers onto reference positions. 3D marker data were interpolated using Matlab and imported into OpenSim 1.9.1. A generic model consisting of 19 DOF (degrees of freedom) was scaled to the anthropometry of the specific subject. Using an inverse kinematics procedure the total body center of mass (COM) was determined. The position of the COM with respect to the heel was then expressed in relation to the marker on the heel and the forefoot marker; a value of 0 represents a COM projection at the heel and is indicative for heel loading whereas a value of 1 indicates a COM projection at the toes and is indicative for forefoot loading.

Statistical Analyses

A Shapiro–Wilk W test was used to assess the normal distribution for all of the studied accelerations, frequencies and RMS. In case of non-normal distribution, non-parametric statistics (Wilcoxon test) were used. In case of normal distribution, the effect of parameter settings of the vibration or position on the vibration transmission were analyzed by one-way and repeated measures ANOVA, Tukey post-hoc testing. All values are reported as mean ± standard deviation (SD). The level of significance was set at $P<0.05$.

RESULTS

All subjects completed the full protocol successfully. None of the participants reported side effects due to the vibration. None of the subjects felt any discomfort, dizziness or fatigue during the vibration session.

The total harmonic distortion of the platform was approximately 2%, showing that the vibration signal delivered by the platform was in all cases sufficiently sinusoidal.[20] The vertical accelerations delivered by the platforms are shown in table 1.

Table 1. Platforms 1 and 2 are adjusted platforms; Platform 3 is the ‘’normal’’ vibration platform. The accelerations were measured on loaded platforms.

Frequency, Hz	*Peak acceleration, g*					
	1 / low	*1 /high*	*2 /low*	*3 /low*	*2 /high*	*3 /high*
30	0.33	0.54	1.23	2.25	3.54	4.50
35	0.40	0.69	1.56	2.99	4.62	5.87
40	0.50	0.93	1.97	3.70	5.89	7.21
50	0.70	1.38	2.90	5.53	7.64	7.98

The transmission of vibration signal from the platform through the entire body followed the same declining curve for all of the studied accelerations and frequencies, and postures (fig. 1).

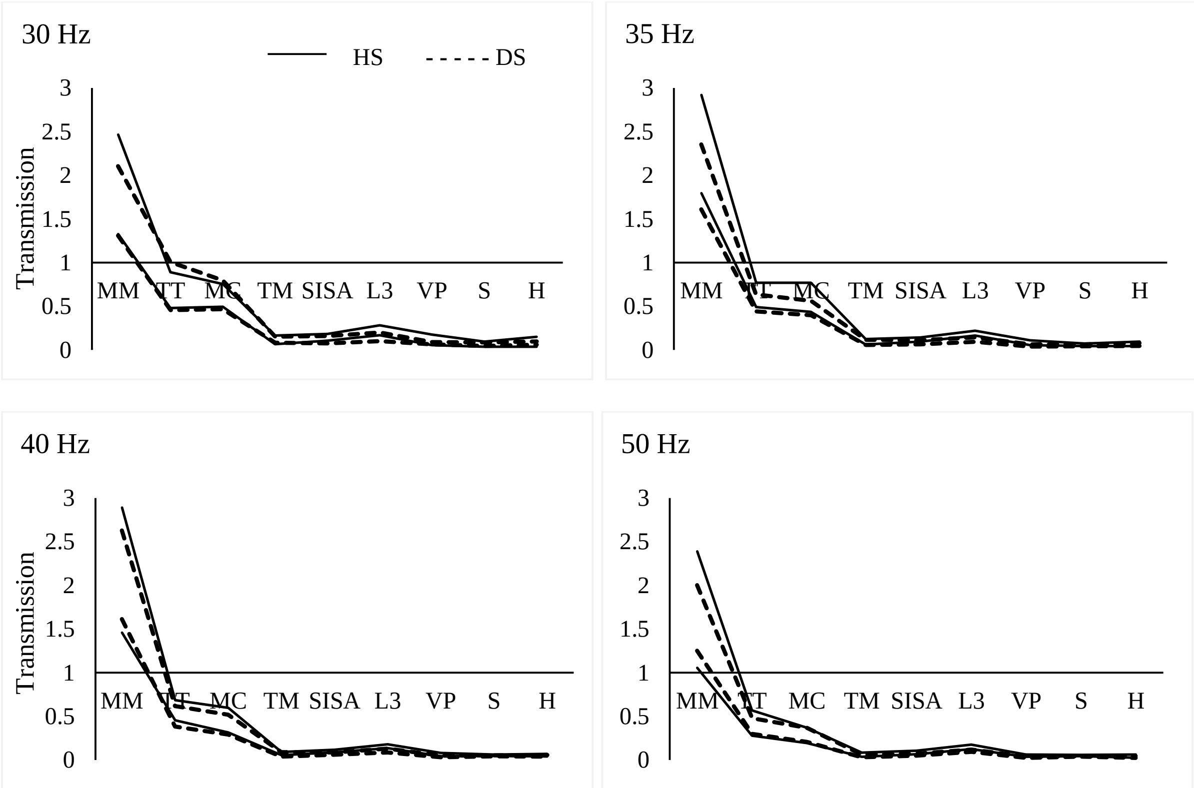


Figure 1. The range of vibration transmission at different frequencies for both squat positions. The transmission of the vibration at the medial malleolus exceeded the RMS of the platform but the signal was attenuated at medial femur condyle. At the knee, the hip and the trunk the transmission of the stimulus was further reduced for all positions.

The transmission of the vibration at the medial malleolus ranged between 1.25 and 2.9 times the RMS of the platform and was significantly attenuated at medial femur condyle. Above the knee, the average transmission of the stimulus was further reduced at the hip – between 0.04 to 0.17 times and at the head – between 0.03 to 0.15 times RMS of the platform, respectively. No significant difference in transmission through the body was found between two squat positions. The deep squat significantly attenuated the vibration only at L3 compared to the high squat ($P<0.05$). The average transmission at L3 ranged between 0.09 to 0.20 times during deep squat and between 0.13 to 0.28 times RMS of the platform during high squat, respectively. Comparing knee bent posture to erect stance, the vibration transmission of the greater trochanter, the trunk and the head during both squat postures was significantly lower compared to the erect stance (P<0.05) (fig. 2). The transmission at (L3) reached 40% (0.42 times) of platform RMS for the erect stance.

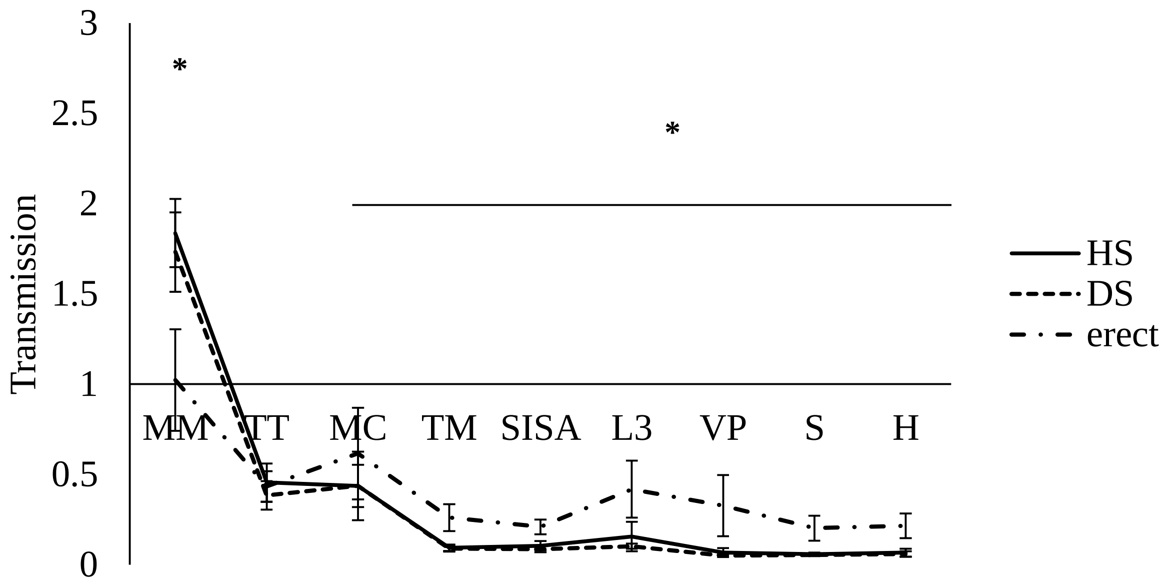


Figure 2. The vibration transmission through the entire body at a frequency of 40 Hz, platform acceleration of 0.50 *g* (mean ± SD). **HS** – high squat, **DS** – deep squat, **erect** – erect stance position.

The weighted RMS (Aeq), the equivalent continuous acceleration over an eight-hour period A(8), the time to reach the daily exposure action value (EAV), and the time to reach the daily exposure limit value (ELV), respectively, are presented in table 2.

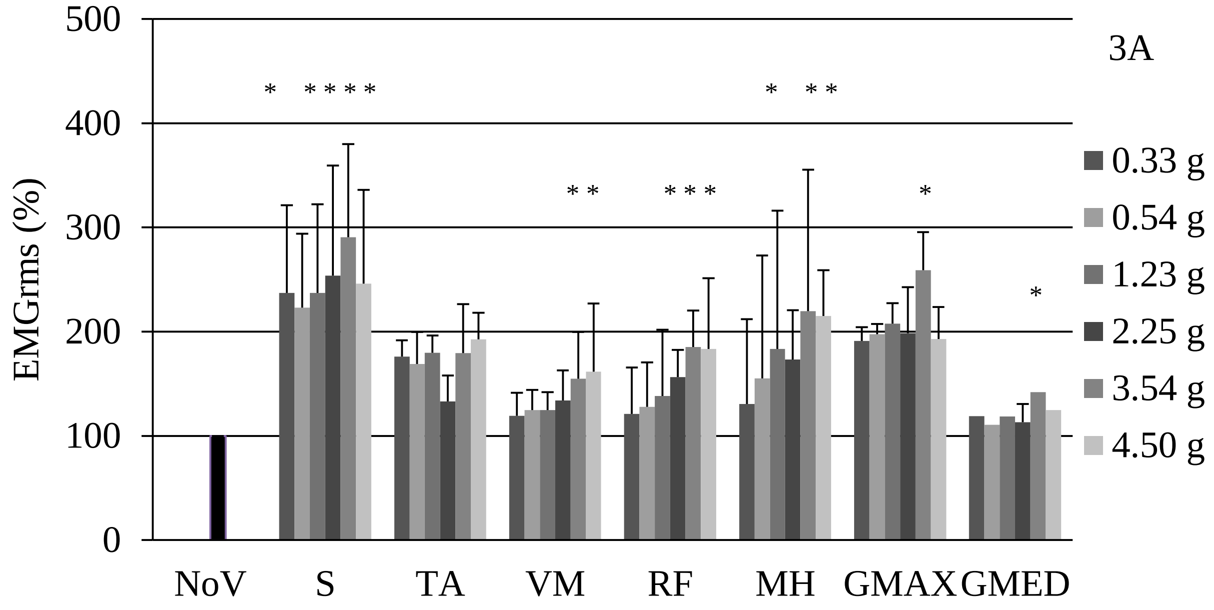
In case of the low acceleration setting of the commercially available platform (2.25 – 5.53 *g*), the vibration platform could be used between 1.38 and 3.12 minutes before the EAV was reached (between 7.35 and 16.45 minutes before the ELV is reached). In case of the highest acceleration of 7.98 *g* – high frequency setting (50 Hz), it took only 20 seconds to reach the EAV and 1.71 minutes to reach the ELV.

Table 2. A representation of the amount of time a subject can use the commercially available vibration platform

Platform	*Acceleration [g]*	*Frequency [Hz]*	*Aeq [m/s²]*	*A(8) [m/s²]*	*Seconds to reach EAV*	*Seconds to reach ELV*
<u>*Low mode*</u>	2.25	30	6.21	0.20	187	987
	2.99	35	6.99	0.23	147	779
	3.70	40	7.66	0.25	123	649
	5.53	50	9.29	0.30	83	441
<u>*High mode*</u>	4.50	30	12.55	0.40	46	242
	5.87	35	13.93	0.45	37	196
	7.21	40	15.80	0.51	29	152
	7.98	50	19.21	0.62	20	103

NOTE. Low mode: 2.25 – 5.53 *g* and high mode: 4.50 – 7.98 *g*, at a certain setting within the safety regulations of the EC (Aeq = the effective RMS, A (8) = eight-hour period acceleration, seconds EAV = seconds to Exposure Action Value, seconds ELV = seconds to Exposure Limit Value). Only 20 seconds are needed to reach the EAV when acceleration increases to 7.98 *g*.

The EMG responses to vibration at the different accelerations tested are expressed relative to EMG of the individual muscles in the non-vibration period (an example fig. 3A).



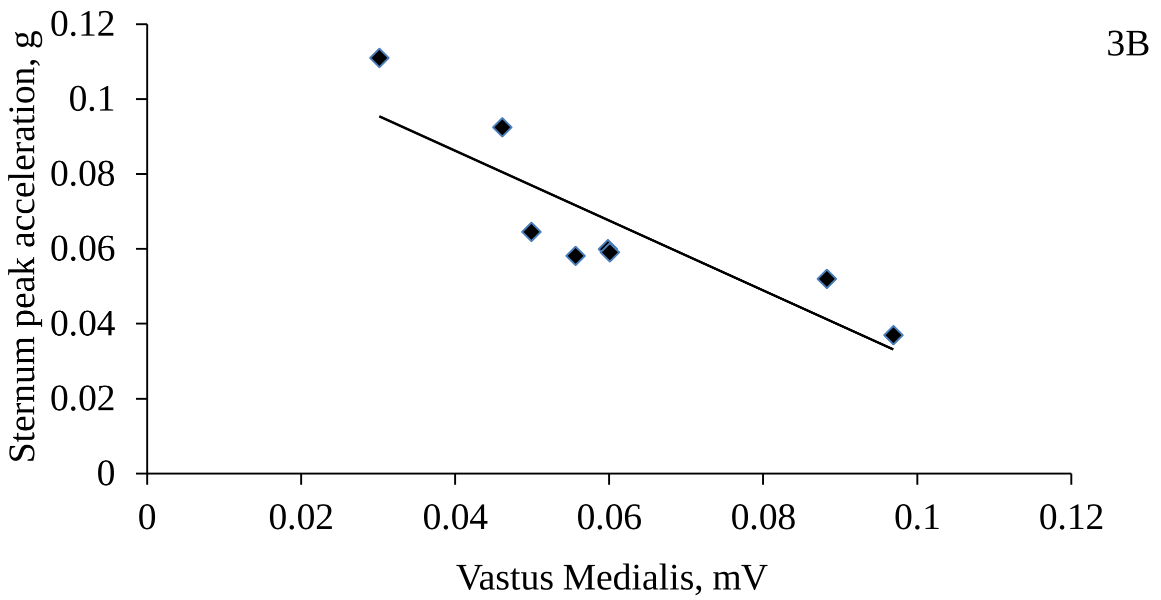


Figure 3. An example of the relationship between the applied vibration acceleration and the muscular activation, 30 Hz, 0.33 – 4.5 *g*, high squat, no-notch filter. The increase in the acceleration did not end in well-defined increase in EMGrms (%). Muscle activity increased significantly when the vibration was applied ($P<0.01$) (fig.3A). The increase in the muscle activation of vastus medialis did result in well-defined decrease in the peak acceleration at the sternum ($P<0.05$), high squat, no-notch (fig.3B). Figure legend: **NoV** – No-Vibration, **S** – solues, **TA** – tibialis anterior, **VM** – vastus medialis, **RF** - rectus femoris, **MH** – medial hamstrings, **GMAX** – gluteus maximus, **GMED** – gluteus medius

Large individual differences in the EMGrms (a ratio 3:1 or more) were found for all of the studied accelerations and frequencies. The use of both approaches – without and with notch filter showed a significant increase in the EMG activity for most of the studied muscles during vibration (average range of 103 – 384.9%). However, the application of notch filter showed a tendency to blur the differences between non-vibration and vibration periods and to decrease the number of the significant values. Irrespective of which filter was used the EMG activity of soleus, vastus medialis, medial hamstrings and gluteus maximus was significantly increased in most conditions.

No significant difference in the muscle activity between the two squat positions during the vibration training was found for any of the muscles in any conditions without and with notch filtering ($P>0.05$). The EMG results during erect stance trials – 35 Hz/ 0.40 *g*, and 40 Hz/ 0.50 *g*, are not reported due to lost EMG contact during the training for most of the subjects.

No clear dose-response relationship was observed between the peak acceleration delivered by the platform and the size of the muscle response with and without notch filtering (fig. 3A).

Muscular activity of vastus medialis and vibration acceleration to the sternum showed a clear negative correlation, almost always significant (range between -0.42 < r < -0.86 for all trials, both squats, with and without notch filtering) (example fig. 3B). Similar negative correlation was found between the muscular activity of rectus femoris and vibration acceleration to the sternum (range between -0.25 < r < -0.41 for all trials, both squats).

The inverse kinematics showed no clear relationship between the individual COM projection and the vibration transmission or the muscular activity (fig. 4).

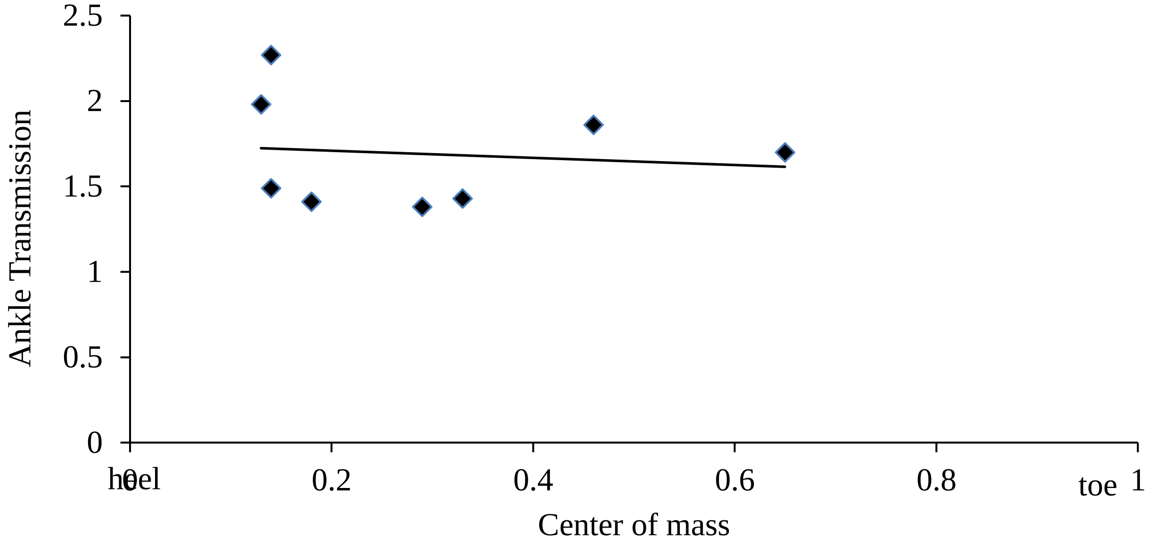


Figure 4. Demonstration of the relationship between the individual center of mass and the vibration transmission at the ankle (n = 8), 50 Hz, 2.90 *g*, high squat. The subjects presenting more heel loading (COM close to 0) did not receive higher accelerations at medial malleolus or the tuberositas tibiae compared with the subjects loading more their toes (COM close to 1) (P>0.05).

DISCUSSION

This is the first study documenting the transmission of a wide range of vibration accelerations and frequencies through the entire body and the associated muscle response, body posture and inverse kinematics.

The major findings were a significant amplification of the acceleration at the ankle and a significant attenuation at the knee and above compared to the one delivered by the platforms. Higher accelerations obtained at the medial malleolus compared to the platform could be explained, on one hand, by the fact that the ankle vibrated in vertical and horizontal directions and on the other hand, saturation might have occurred in the signals of the ankle. Comparable increase in acceleration at the ankle was previously reported by Kiiski et al.[12] However, they also found an amplification of the acceleration at the knee, the hip and the spine when vibration frequency ranged between 10 – 25 Hz. Similar amplification of the signal was shown by Pollock et al.[14] (vibration frequency between 5 – 30 Hz), although the vibration platform used in their study delivered the signal side-alternating and the acceleration was recorded using 3D motion analysis. Both studies applied vibration frequency below 30 Hz and as a result of body resonance, the vibration acceleration might be amplified up to the spine.[15] This might cause body overloading, especially in elderly individuals with a fragile spine and hip.

In the present study, the transmission to the spine (L3) was 40% for the erect stance (only measured at low vibration amplitude) and ranged between 13 – 28 % for high squat and 9.0 – 20% for deep squat positions, respectively. In comparison, Rubin et al. (2003) reported a blunting of the transmission to 75% and above 50% of the original platform signal at the spine during vibration at a frequency of 35 Hz for the erect position and the 160° knee flexed position, respectively.[15] At a similar acceleration and frequency, the transmission of the signal in our study was lower than in the one by Rubin. This difference might be partly related to the fact that we used skin-mounted accelerometers, while Rubin et al. (2003) used bone-mounted accelerometers which are more accurate, but also more invasive. Furthermore, in the present study, WBV clearly evoked a muscular response that might result in additional damping of the vibration signal and further reduce the transmission. The damping effect of vastus medialis and rectus femoris showed clear tendency to alter the transmitted vibrations to the upper part of the body. Finally, apart from muscular activation, the human body regulates the acceleration transmission through joint kinematics.[21] In our study, subjects performed deeper squat positions (135° and 110°) than in the study by Rubin (160°) and this may again have contributed to the lower transmission we found. The performed different squat positions could affect the spine stabilization, the damping effects of the joints and trunk muscle activation. Furthermore, the deep squat attenuated the transmission of the acceleration at L3 compared to high squat, suggesting that the use of deeper squat during vibration training might reduce the risk of overloading the spine. However, to keep the subject’s position during the trials, we used visual feedback, which required a continuous balance control resulting in additional muscle stiffness and increase in the vibration signal.[5] Moreover, the participants held a handle, which additionally increased the stiffness of the trunk and might explain the higher vibration transmission at L3 compared to greater trochanter and SISA. Our findings support previous results of lower transmission of accelerations in a knee bent posture compared to the erect posture.[11] However, only Crewther et al.[22] reported peak accelerations in a semi-squat position (120°) at the knee, the hip and the jaw that were significantly higher when compared to the erect stance. The platform used in their study delivered however the signal side-alternating (the signal was delivered first to one of the legs, then to the other). Additionally, it is important to emphasize that also different vibration parameters (frequency below 30 Hz) were used by Crewther, which could explain some of the inconsistencies.

Several research groups have assumed that platform accelerations exceeding 1 g might be harmful to the body, based on transmission data at the ankle, the hip and the spine.[12,15] However, in the present study the transmission of the acceleration diminished significantly through the body. For example at the highest platform acceleration of 7.98 g only 0.03 times platform RMS reached the head. The vibration exposure techniques to evaluate WBV training regimes have not been extensively studied.[12,23,24] This is partly due to the fact that norm ISO2631 is mostly based on research with vertical vibration of seated persons,[17] with no norm developed specifically for standing persons. Nevertheless, the safety aspect of WBV training seems crucial for evaluation of WBV training regimes. The evaluation guidelines in the European Vibration Directive are meant for occupational exposures, where subjects are usually standing in an upright position, while our subjects had their knees bent with active muscle activation, resulting in significantly lower transmission to the upper body (see figure 1). The exposure limits mentioned in the vibration directive are, therefore, not correctly determined for a WBV training condition and most likely underestimated. In the present study, the commercially available platform (platform 3), with acceleration ranging between 2.25 – 7.98 g shows time to reach the Exposure Limit Value (ELV) between 16.45 and 1.71 minutes. Therefore, use of WBV training on a daily basis for 15 minutes and in a flexed knee position appears reasonably safe, especially when avoiding high amplitude and high frequency settings. However, the exposure to vibration should be evaluated for all emissions throughout the day. Even if exposure to vibrations due to the use of WBV training devices is below the Exposure Action Value (EAV) or the Exposure Limit Value (ELV), it could add up to the WBV exposure during professional activities.

With regard to the muscle activation due to vibration, the present results show that WBV in squat position elicited muscular contraction in all muscles (range between 103 – 384.9% increase compared to no-vibration), even at the lowest accelerations, although not always significantly. This increase in muscle activity varied widely between subjects, which – along with the relatively small sample size – may have contributed to the lack of significance for some results. We confirmed the increase in lower limb muscle activation that has been demonstrated by several WBV studies.[25-29]

We used both band-pass and notch filters to filter EMG, in contrast to earlier studies where EMG was filtered using notch[14,25] or band-pass filter,[29] only. This combined use solves the problem of using band-pass filters only, which may result in an overestimation of the real muscle response caused by motion artifacts due to the vibration.[25,30] It also solves the problem of using notch filters, which may lead to an underestimation of the true magnitude of the muscular response by eliminating real vibration induced motor-unit firings at the vibration filtered frequency.[31] Fratini et al. showed that EMGrms values reduced more than 30% when sharp notch filter was applied, underlining the significant influence of motion artifacts to EMG analysis.[32] The ‘true’ muscle response due to WBV lies in between the two approaches. It should be noted that in the present study, EMGrms (%) was defined relative to the non-vibration period which sometimes resulted in higher EMGrms activity for some muscles when the notch filter was applied. Therefore, the EMGrms obtained with both approaches cannot be compared directly.

In contrast to other studies,[27] we found no clear dose-response relationship between vibration signal parameters and muscle activation. The difference in vibration transmission (~4:1) and in EMG response (~3:1 or more) between the subjects was high. This is not surprising as Kiiski and Harazin[11,12] have even reported variation around 10:1 in transmission. Rittweger[31] suggested that vibration propagation can be diminished by posing more body weight on the forefoot. Hence, posing the body mass more on the toes or on the heels during vibration might explain some of the differences found in the vibration transmission and muscle activation between the subjects. However, we performed 3D analysis of posture using the projection of COM and found no relationship between body posture and vibration transmission. To estimate the load applied to the feet more precisely in future studies, pressure sensors could be used to measure the contact pressure between the foot surface and the vibration platform.[33] The usage of pressure sensors would probably give more accurate information about the position of the body weight during WBV and further elucidate the effect of body posture on the transmitted peak accelerations and possible EMG response.

Study Limitations

Our study has limitations and the results should be interpreted in the context of its design. One shortcoming is the use of skin-mounted accelerometers, allowing movements of soft tissue and skin to potentially interfere with the transmitted acceleration detected by the accelerometers. We did not apply a force plate to measure the center of pressure, which would allow explaining more clearly the differences in vibration transmission from the platform to the ankle. Another limitation is that we only addressed healthy, young subjects and that our data cannot be generalized to other populations. Another drawback is that we only performed a single data-collection session, without re-test, not allowing an assessment of differences in response to vibration within subjects.

PRACTICAL APPLICATIONS

This study is the first to address WBV transmission through the entire body and its relation with leg muscle activity, body posture and inverse kinematics over a wide range of vibration accelerations and frequencies. The subjects performed commonly used exercises (high and low squat) on a commercially available vibration platform. Coaches and practitioners should know that the transmission of high-magnitude accelerations was highly attenuated from the knee up to the head with no dangerous accelerations in any of those body parts. Moreover, both squat postures attenuated additionally the peak accelerations acting at the hip, the trunk and the head compared to erect stance. The specific WBV parameters of individual exercises used in the present study are considered to constitute a safe and suitable vibration exercises when accounting for the total acceptable duration and combining exercises into a training program. For the exercises tested in the present study, the commercially available platform (platform 3, 2.25 – 7.98 *g*) can be used on a daily basis for 15 minutes and in a flexed knee position, especially when high amplitude and frequency settings are avoided.

Additionally, the results of the study show involuntary increase in EMG activity in most muscles of the lower limb up to the glutei. The vibration parameters used in the study induced higher EMG response compared to isometric contractions during 2 different squat positions. Moreover, considering the potential beneficial effects on bone density, we focused on the transmission of the vibration signal at the trochanter major. In the present study, the peak accelerations delivered by the commercially available platform ranged from 2.25 up to 7.98 *g* with a frequency above 30 Hz. In a study of Borer and colleagues,[34] the impact loading of physical exercise needed to improve total BMD was estimated as a peak force greater than 1.22 times body weight (fast walking). Beneficial effects on the skeleton are a product of strain intensity and loading frequency. Bone could be stimulated either with high-magnitude/low-frequency loading or low-magnitude/high-frequency loadings.[35,36] With platform accelerations above 1 – 2 *g* and the use of a frequency > 30 Hz, it seems that the vibration peak accelerations in the current study might be sufficient to increase the BMD of the body.

Acknowledgments

Authors state that they have no conflicts of interest and that the results of the present study do not constitute endorsement of the product by the authors or the NSCA. Grant supports FWO-G0488-08 and FWO KN 1.5.017.08.

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CHAPTER 2

Vibration training for upper body: transmission of platform vibrations through cables

J Strength Cond Res 28(4): 1065–1071, 2014

Ekaterina Tankisheva [1]
Steven Boonen[†, 2]
Christophe Delecluse [3]
Hans Druyts [4]
Sabine M.P. Verschueren [1]

[1] KU Leuven – University of Leuven, Department of Rehabilitation Science, Musculoskeletal Rehabilitation Research Centre
[2] KU Leuven – University of Leuven, UZ Leuven, Department of Experimental Medicine
[3] KU Leuven – University of Leuven, Department of Biomedical Kinesiology, Research Centre for Exercise and Health
[4] Custom8 NV – Biomechanics Section, Belgium

ABSTRACT

The aim of the present study was to evaluate the vibration transmission from a vibration platform through vectran cables to the upper body and its relationship to induced muscular activation.

Fifteen clinically healthy participants performed 3 different arm exercises – biceps curl, triceps curl, and lateral raise. Vibration transmission to the upper body was assessed over a wide range of accelerations (from 1.90 to 5.98 *g*) and frequencies (from 25 to 40 Hz). To assess the vibration transmission, seven tri-axial accelerometers were attached from the hand up to the head and the root-mean-square (RMS) of acceleration signal of each site-specific body point was calculated. Muscular activity of biceps brachii, triceps brachii, deltoid and upper trapezius was recorded.

The results showed a significant attenuation of the platform accelerations transmitted through the vectran cables to the upper body. Handle vibration ranged between 27 – 44 % of the acceleration delivered by the platform depending on platform vibration parameters (acceleration/frequency). Vibration increased the muscle activity of biceps brachii, triceps brachii, deltoid and upper trapezius muscles significantly only during biceps curl exercises. No frequency and/or acceleration effect was found on the size of the muscle response.

The results of the present study suggest that a cable-pulley resistance system on a vibration platform channels the vibration safely from the platform to the arms and induces additional muscle activation in some arm muscles when biceps curl exercises are performed.

Key words: muscle activation; tonic vibration reflex; acceleration; biceps curl.

INTRODUCTION

Whole-body vibration (WBV) training has emerged as a potential alternative for, or addition to, traditional resistance training, with increasing evidence for WBV-induced improvements in leg muscle performance in athletes,[1] sedentary adults[2] and elderly.[3]

Vibration stimulates the Ia-afferents of muscle spindles that in turn activate α-motoneurons in a reflexive manner, known as tonic vibration reflex (TVR).[4] Vibration stimulates the activity of lower-limb muscles[5] and can therefore be used to "exercise and train" these muscles. Additionally, inhibition of the agonist-antagonist co-activation by Ia-inhibitory neurons might be involved when activating the muscles through vibration.[6]

Only a few studies have investigated the effect of WBV on upper limb and trunk muscles,[7-9] typically reporting low or no effects on upper body muscle performance. A major reason for this lack of effect is the attenuated vibration stimulus that reaches the upper limbs due to the distance between the vibration platform and the target muscles and the damping properties of the human body.[7,10] As a result, WBV devices designed for lower-limb muscle training may be unsuitable for arm muscle stimulation.

Different tools such as vibrating dumbbells,[11] a muscle-tendon vibrator[12] or a vibratory stimulation device attached to a pulley system[13] have been tried to enhance transmission of the vibration stimulus to the upper body and improve upper body muscular performance. Bosco et al.[11] reported an increase in muscular activation of biceps brachii when vibrating dumbbells were used. In contrast, Moran et al. showed no effect of vibration stimulation on muscle activity during dynamic biceps curl when vibration was delivered by a portable muscle-tendon vibrator attached over the biceps tendon.[12] Overall, the effects of vibration on arm and trunk muscular activation remain controversial and inconclusive.

In this context, we tested a new vibration device with cable-pulley resistance system attached to a vibration platform, in an attempt to channel the vibration indirectly from the platform to the upper body and potentially broaden the impact of training to the whole body. Thus, the specific aim of our study was to assess the muscle activation of arm and trunk muscles while performing different static and dynamic arm exercises with a cable-pulley resistance system. We evaluated the vibration transmission through the cables to the upper body and identified dose-response relationships between vibration parameters and induced muscle activation. First, we hypothesized that the vibration transmitted through the cables would evoke higher muscle activation of the arm and trunk muscles than the same exercises performed without vibration. Second, the different vibration parameters delivered by the platform would be considered as safe and would result in different muscle response.

METHODS

Experimental Approach to the Problem

Vibration transmission was evaluated over a range of vibration frequencies (from 25 to 40 Hz) and accelerations (from 1.90 to 5.98 *g*) while the accelerations of several body points were measured during different dynamic and static exercises. Additionally, the EMG of different muscle groups was recorded.

Subjects

Fifteen clinically healthy volunteers (7 males and 8 females; age 27.4 ± 4.6 years; height 1.73 ± 0.07 m; body mass 65.2 ± 6.8 kg) participated in the study. All participants gave full informed consent to participate in the vibration training protocol approved by the Leuven University's Human Ethics Committee according to the declaration of Helsinki. None of the participants had previously participated in any studies of whole-body vibration. The subjects were informed about the purpose of the study, and about the possible risks and benefits of the training. They were free from any muscular injuries or musculoskeletal diseases.

Procedures

The vibration exercises were performed on a commercially available WBV platform which induced synchronous vertical vibrations at frequency of 25, 30, 35 and 40 Hz and two amplitude settings ('high' and 'low') (Power Plate pro 6TM, Badhoevedorp, The Netherlands). The platform had an additional cable-pulley resistance system of high strength vectran cables to transmit vibrations to the upper body. The resistance of the cables was adjustable which resulted in two different resistances during performance. The low resistance corresponded to 2.5 kg and the high resistance to 5 kg, respectively, as measured with a peak-hold dynamometer.

All subjects participated in a single data – collection session and were encouraged to immediately report any unusual symptoms (e.g., discomfort, dizziness) during the vibration training. Subjects wore only socks to diminish the damping of the vibration due to the footwear.[14] The protocol was organized in 9 different series: 8 vibration series – four frequencies (25, 30, 35, 40 Hz) x two amplitude settings ('high' and 'low') and one non-vibration series including the same exercises but without vibration. Each series included four different exercises: two biceps curl exercises, a triceps curl and a lateral raise exercise (fig. 1).

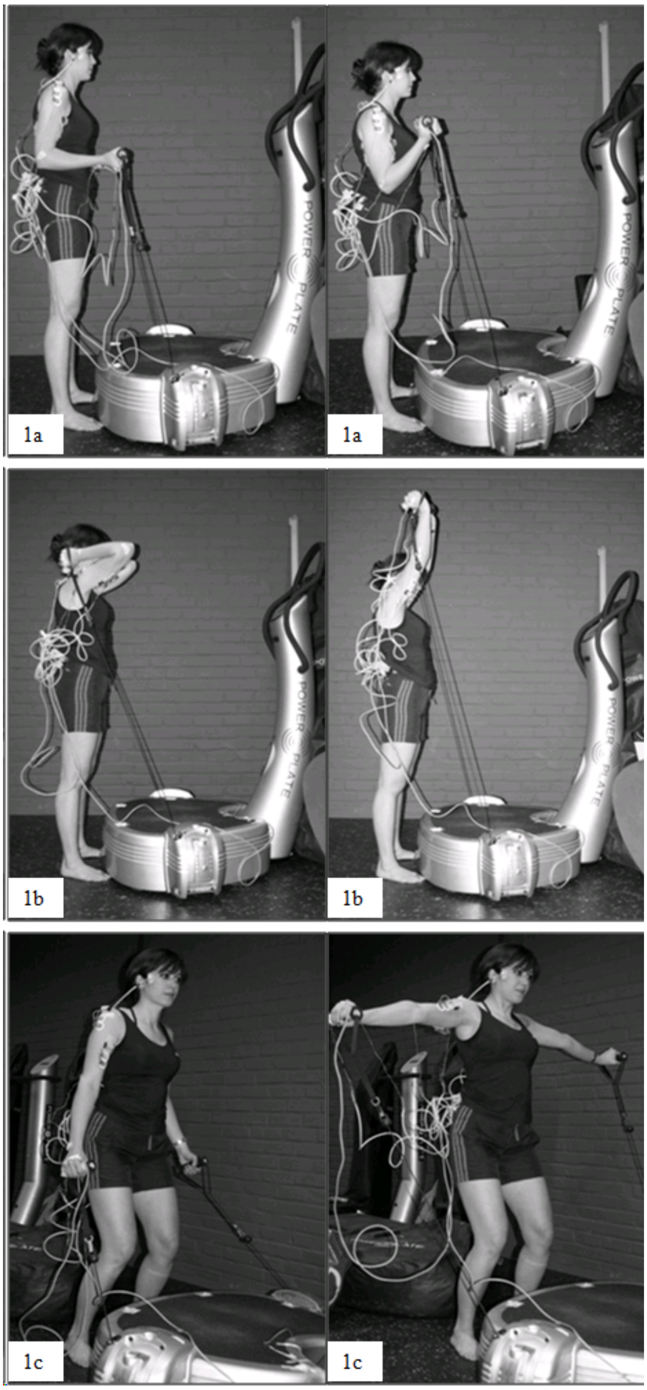

Figure 1. Dynamic exercises performed during the vibration training: a) 90° dynamic biceps curl b) dynamic triceps curl c) 90° dynamic lateral raise in knee bent position (knee angle of 135°).

Biceps curl exercise

The participants performed a 90° dynamic biceps curl exercise against low resistance and a 90° dynamic biceps curl exercise against high resistance (figure 1a). The subjects performed additionally a 70° static biceps curl exercise for 60 seconds behind the platform only at 40 Hz, high amplitude mode, high cable resistance.

Triceps curl exercise

The participants performed a dynamic triceps curl against low resistance (figure 1b).

Lateral raise exercise

A 90° dynamic lateral raise exercise against low resistance was performed (figure 1c). During lateral raise exercises the subjects performed a knee squat position of 135 ° (whereby 180° means fully extended knees). To ensure the correct knee positioning of 135°, the knee angle was measured with a goniometer before each trial.

None of the participants was previously involved in any arm-trunk exercise programs and therefore, to maintain the protocol within reasonable limit, the triceps curl and lateral raise exercises were performed only against the lower resistance. The exercises were performed while the subjects were standing behind the platform. Each exercise was performed at the same pace of a metronome (60 beats per minute). The participants were instructed to hold the handles firmly in their hands. To avoid influence of fatigue in the measurements, for each subject, the series were randomized and a sufficient rest of 2 minutes was provided between series.

Specific equipment

Seven tri-axial SMB380 accelerometers were used to measure the vibration accelerations at the 3rd metacarpal bone (hand), styloid process of the ulna (wrist), medial epicondyle of the humerus (elbow), acromion (shoulder), vertebra prominens (C7), manubrium of the sternum, and head. The accelerometers were adhered to the subject’s skin using adhesive tape. All cables were secured by bandages to prevent swinging and movement-induced artifacts. The weight of each accelerometer was 0.6 g and the size 12 mm x 14 mm x 2.5 mm (WxLxH). The calibration of the SMB accelerometers was checked against a standard piezo-accelerometer, revealing a linear relationship up to a magnitude of 7 *g*. Additional two tri-axial SMB accelerometers were placed on the platform and the handle to provide accurate data on the different platform accelerations during the exercise. One uni-axial piezo-accelerometer provided accurate vertical peak accelerations delivered by the platform. Vibration signals were analyzed using Matlab. All accelerations were sampled at 1 kHz. Raw signals were filtered using a high pass 8th order Butterworth filter (10Hz) with a zero-phase forward and reverse filtering (zero phase distortion). The root-mean-square (RMS) of acceleration signal at the platform, the handle and the different body points were calculated. The platform-handle transmission was defined as a ratio of RMS acceleration of handle to the RMS acceleration of the vibration platform. The handle-body transmission was determined as a ratio of RMS acceleration of a site-specific body point to the RMS acceleration of the handle.[15]

To evaluate the safety aspect of vibration training, a basic evaluation method from ISO5394-1:2001 was followed.[16] The vibration exposure was evaluated by comparing the A(8) value (8-hour energy-equivalent frequency-weighted acceleration) to a daily Exposure Action Value (EAV, 0.5 m/s^2) and a daily Exposure Limit Value (ELV, 1.15 m/s^2). The time to reach the EAV or the ELV during an each vibration session was calculated from A(8) value and the weighted root-mean-square acceleration – Aeq.

During the experimental session, a wireless surface EMG system (Zerowire, Aurion Italy) was used to record the muscle activity of the right biceps brachii, triceps brachii, deltoid and upper trapezius. The bipolar surface EMG electrodes were mounted to the arm and back with double-sided contact tape and fixed using adhesive tape to guarantee their position and contact during the vibration. The skin was prepared by abrasion, shaving and alcohol cleaning to ensure a better contact. To avoid crosstalk caused by EMG signals coming from neighboring muscles, the electrodes were placed at the middle of the muscle belly and an appropriate inter-electrode (center-to-center) distance of 20 mm was chosen. EMG-signal validity was checked visually before starting the EMG-recording.[17] The EMG signals were amplified and sampled at 1000 Hz. The root-mean-square (EMGrms) was calculated for both non-vibration and vibration trials. The EMG was analyzed by two different approaches – 1) only band-pass filters (between 10 and 500 Hz) were applied and 2) an additional sharp band-stop (notch) filter. The notch filter was implemented to eliminate possible artifacts at the exact excitation frequency of the platform working at 25, 30, 35 and 40 Hz, respectively. An average root-mean-square (RMS) was calculated for non-vibration and vibration periods.

Statistical Analyses

The dependent variables in the different statistical tests were EMGrms, RMS of the acceleration, and platform-handle and handle-body transmission. A Shapiro–Wilk W test was used to assess the normal distribution for all of the studied accelerations, frequencies and RMS. In case of non-normal distribution, non-parametric statistics (Wilcoxon test) were used. In case of normal distribution, the effect of parameter settings of the vibration or position on the vibration transmission were analyzed by repeated measures ANOVA, Tukey post-hoc testing. All values are reported as mean ± standard deviation (SD). The level of significance was set at $P < 0.05$.

RESULTS

All subjects completed the full protocol successfully. None of the participants reported any side effects due to the vibration or felt any discomfort, dizziness or fatigue during the training. Table 1 shows the vertical peak accelerations (g) and peak-to-peak amplitude (mm) delivered by the platform and measured with an accelerometer with respect to the different frequencies (where g is the Earth's gravitational field of 9.81 m/s^2).

Table 1. The peak acceleration (*g*) was measured with an accelerometer.

Frequency, Hz	Low amplitude mode		High amplitude mode	
	Peak acceleration, *g*	Peak-to-peak amplitude, mm	Peak acceleration, *g*	Peak-to-peak amplitude, mm
25	1.90	1.51	3.26	2.59
30	2.02	1.12	3.66	2.02
35	2.84	1.15	4.73	1.92
40	3.60	1.12	5.98	1.86

NOTE: The peak-to-peak displacement amplitude was computed from the acceleration amplitude: $X = A/w^2 = A/ (2.pi.f)^2$, where A is peak-to-peak acceleration and f – the frequency.

The average handle acceleration varied between 0.33 – 1.33 *g* for all exercises, meaning that the average vibration transmission from the platform to the handle ranged between 27 % – 44 % RMS acceleration of the platform. There were no significant differences in transmission to the handle between the different exercises.

The average vibration transmission from the handle through the arm and the trunk followed a similar declining curve for all of the studied parameters and exercises (an example in figure 2).

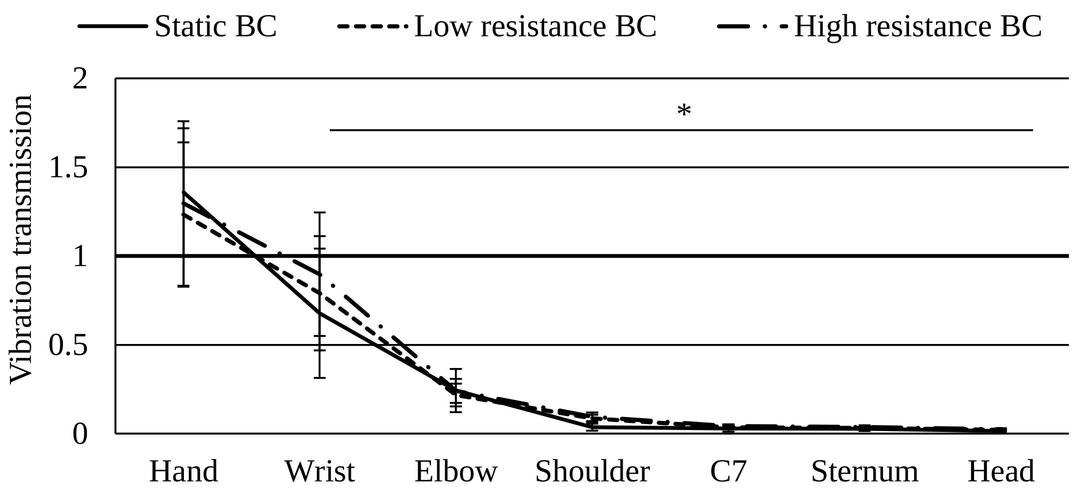

Figure 2. The average vibration transmission from the handle through the arm and upper body at a frequency of 40 Hz, platform acceleration of 5.98 *g* during biceps curl exercise (**BC**).

The average transmission of the vibration at the 3rd metacarpal bone (hand) ranged between 0.93 and 1.41 times the RMS acceleration of the handle and was further up significantly reduced at the arm and the head. The RMS acceleration at the head never exceeded accelerations higher than 0.25 *g*. No significant difference in transmission was found between the different accelerations and frequencies within each exercise.

According to the calculations based on ISO5394-1:2001[16] the total weighted acceleration never exceeded 0.85 *g*. The total vibration dose A(8) ranged between 0.35 and 0.45. This would imply that the specific exercises performed in the present study could be maintained 42 minutes before the daily Exposure Action Value (EAV, 0.5 m/s^2) was reached, and 172 minutes before the daily Exposure Limit Value (ELV, 1.15 m/s^2) was reach.

According to muscle response, the use of both approaches – without and with notch filter showed a significant increase in the EMG activity for most of the studied muscles during vibration. No significant difference in EMGrms with and without notch filtering was found, however, the application of notch filter showed a tendency to blur the differences between non-vibration and vibration periods and to decrease the number of the significant values. Thus, all results are presented as mean EMGrms +/- SD without notch filtering. The EMG responses to vibration at the different accelerations tested were expressed relative to EMG of the individual muscles in the non-vibration period, normalization relative to maximal voluntary contraction was unnecessary[5]

Biceps curl exercise

As can be seen in figure 3a, vibration induced a higher muscle activity in biceps brachii, triceps brachii, deltoid and upper trapezius compared to non-vibration EMGrms during static biceps curl exercise ($P < 0.05$).

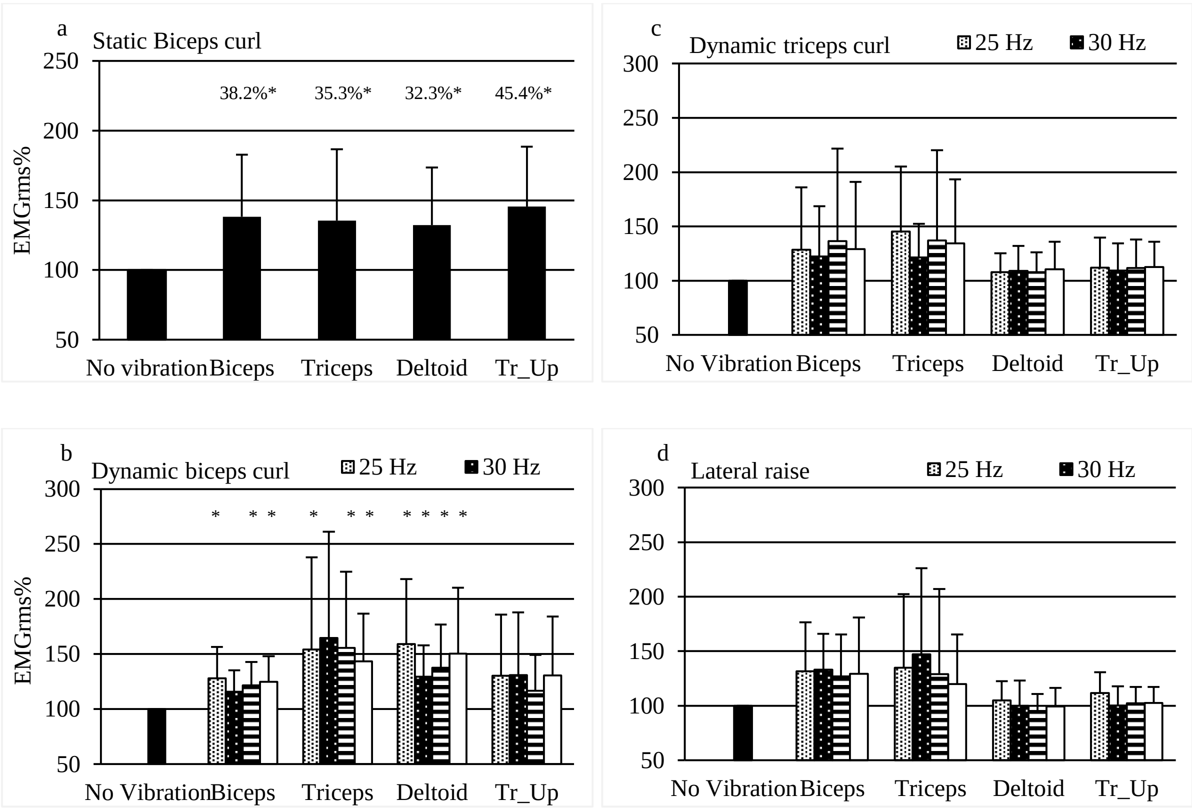

Figure 3. (a) Vibration induced a higher muscle activity in biceps brachii, triceps brachii, deltoid and upper trapezius (Tr_Up) compared to non-vibration EMGrms during static biceps curl ($P < 0.05$). The parameters of the applied vibration: frequency of 40 Hz, platform acceleration of 5.98 *g*. (b-d) An example of the relationship between the applied vibrations during dynamic biceps curl, triceps curl and lateral raise (frequencies of 25 – 40 Hz, platform accelerations of 3.26 – 5.98 *g*, high resistance, no-notch filter). * indicates a greater muscle activity during vibration compared with non-vibration ($P < 0.05$).

The EMGrms measured during dynamic biceps curl resulted in a significant increase in EMGrms of biceps brachii (range between 14 – 30.4 %), triceps brachii (range between 29.6 – 84.6 %) and deltoid (range between 24.3 – 59.1 %) due to vibration in most of the studied conditions ($P < 0.05$) (an example in figure 3b). No differences in EMGrms of different muscles between static and both dynamic biceps curl exercises were found ($P > 0.05$) when frequency was set up at 40 Hz, high acceleration mode. Different cable resistance (low and high) did not result in different muscle activation for any of the studied muscles ($P > 0.05$).

Triceps curl exercise

EMG activity of biceps brachii and triceps brachii measured during dynamic triceps curl ranged between 22.2 – 60.2 % and 7.8 – 60.1 %, respectively of non-vibration EMGrms, but no significant difference between vibration and non-vibration was found for any of the studied muscles ($P > 0.05$) (an example in figure 3c).

Lateral raise exercise

No increase in EMG was found for any of the muscles compared to non-vibration while performing dynamic lateral raise during all studied accelerations and frequencies ($P > 0.05$) (an example in figure 3d).

There were no significant frequency and/or acceleration main effects in all conditions. No clear dose-response relationship was observed between the acceleration and frequency of the platform or the handle and the size of the muscle response with and without notch filtering.

DISCUSSION

To our knowledge, this is the first study to report vibration transmission through a vectran cable-pulley resistance system on a vibration platform to the upper body in a wide range of vibration accelerations and frequencies and its relationship to muscular activation during different dynamic and static exercises.

The outcomes of the present study confirmed the hypothesis that the vibration delivered through the cables can be considered as safe. The vibration delivered by the platform that reached the handle ranged between 27 % – 44 % depending on platform vibration parameters (acceleration/frequency) and might be affected by the different angles of the vectran cables in different exercises, the distance and the orientation of the handle with respect to the platform.[18] Irrespective of the exercise, an amplification of the signal was found at the hand and ranged between 0.93 and 1.41 times the RMS acceleration of the handle, which could be explained by the fact that saturation might have occurred in the signals of the hand. The accelerations entering the body through the handles were not constant during the different exercises but dependent on the movement of the cables, the handles and the hand. Vibration transmission might be affected by the grip strength on the handle. Moreover, the small changes in hand-arm orientation could significantly alter the energy absorption and vibration transmission due to both rotational movements of lower arm bones and of elbow joint.[19,20] Additionally, during arm exercises, the person typically combines several exercises with different movements of the handles, which influences the total vibration dose differently. In the present study, the total weighted acceleration never exceeded 0.85 *g*. Around 42 minutes would be needed before the daily EAV was reached, and 172 minutes before the daily ELV was reach. As this is far beyond the typical duration of arm exercises, the vibration training used in the present study seems reasonably safe and might be considered for daily vibration training. Moreover, the results on total weighted acceleration value showed that the exercise has only a modest contribution to the vibration dose the subject is allowed to receive.

The current results partly confirm the hypotheses that muscle activation of the arm and trunk muscles would be higher during vibration exposure. An increase in EMGrms of biceps and triceps brachii, and deltoid was found due to vibration only during dynamic and static biceps curl exercises. No effects on muscle activity of any of the muscles were found during dynamic triceps curl or lateral raise exercises. This might be due to the different direction of arm movements in relation to the direction of the vibration signal. Biceps curl exercises were in the line of the vibration while lateral raise and triceps curl exercises were presumably at an oblique angle with respect to vibration direction.

Muscular performance as a result of vibration stimulation might be influenced either by muscle fatigue or by a post-activation potentiation. In the present study, fatigue caused by the vibration training is very unlikely due to the short vibration exposure, the provided rest periods and the randomization of the different series between subjects. Moreover, none of the participants experienced the exercises as fatiguing.

In the current study the muscle performance might have been influenced by a post-activation potentiation. Previously it has been shown that acute whole-body vibration could cause a post-activation potentiation of muscle twitch potentiation which resulted in higher muscular activation after vibration stimulation compared to non-vibration.[21,22]

Different resistances of the pulley system (2.5 kg – low resistance and 5 kg – high resistance) did not show any difference in muscle response in any of the muscles irrespectively of the vibration parameters. It has previously been suggested that an additional loading during vibration may alter muscle stiffness and tension and thus, the vibration transmission through the body and the induced muscle activation.[23] However, in the present study no differences in vibration transmission or muscular activation have been found with respect to the resistances of the pulley system. It should be emphasized that the subjects did not performed exercises without resistance and the 'real' effect of resistance on muscle activation and vibration transmission is unknown, and thus, the resistance of the pulley system might be not sufficient to induce additional muscle activation.

In line with our findings, Mischi and Cardinale[23] found an increase in EMG activity at both the biceps and the triceps brachii, during isometric elbow flexions and extensions, but they used a frequency of 28 Hz delivered by an adapted industrial motor magnet and the vibration was transmitted through a lever to a hand grip. They concluded that both muscles are more sensitive to vibration stimulation during extension compared to flexion exercises. In the current study, we only used static flexion and dynamic flexion-extension exercises and, by design, we were unable to compare extension and flexion. Similar static flexion biceps exercises were performed in the study of Bosco et al.[11] where the EMG activity of biceps brachii increased around 100% during vibration compared to non – vibration, which is higher than in our findings (38.2 %). It should be underlined that they delivered vibration directly to the hand by a vibrating dumbbell (dumbbell acceleration of 3.4 g) compared to present study (handle acceleration of 1.34 g or 37.1 % of RMS acceleration of the platform) and allowed more vibration to reach the biceps. In a recent study of Marin et al.,[8] a hand strap attached to a WBV platform was used to target the biceps brachii muscle. A significant increase of 27.7% in muscular activity of the biceps was reported while a target group of elderly stood on vibration platform. The increase in EMGrms was somewhat lower compared to our study and the acceleration that reached the hands was not measured.

In the present study, we did not confirm the hypothesis that the different vibration parameters delivered by the platform would evoke different muscle response. No real frequency and/or acceleration effect was found on the size of the muscle response with or without notch filtering. In another WBV study, Marin et al. showed no difference in muscle activation of biceps brachii between frequencies of 30 and 46 Hz during static biceps curl.[8] In contrast, Hazell et al. reported the highest EMG response of triceps brachii when a frequency of 45 Hz (compared to 25, 30, 35 and 40 Hz) was applied and static biceps curl was performed during WBV.[7] In the present study, our frequency did not exceed 40 Hz and no frequency effect was found, probably because of the different vibration approach, the limited vibration transmission at the handle and the high variance in the EMG response.

Study Limitations

Our study has limitations and they should be interpreted in the context of its design. First, the subjects only participated in a single data-collection session and we did not assess differences in response to vibration within subjects. Second, we only addressed healthy, young subjects and we acknowledge that our results cannot be generalized to other populations. Third, we applied only skin-mounted accelerometers which allow movements of soft tissue and skin that potentially interfere with the transmitted acceleration detected by the accelerometers. Fourth, the rest of 2 minutes provided between the vibration series might have been insufficient to avoid the crossover of the effects of the vibration on the next training series. Finally, although, the participants performed commonly used exercises, the present findings cannot be generalized about other arm or trunk exercises typically used during resistance training. The effect of the vibration on triceps brachii muscle activation might have been higher if the participants were facing away from the platform as a result of the increased range of motion during triceps curl exercise. Moreover, vibration stimulation during lateral raise exercises might have been more efficient if the cables were drawn across the body, which could have also resulted in increased range of motion and higher muscle response, respectively. Further studies should focus on more broad combinations of arm and trunk exercises to be able to provide a better insight on how the different vibration training protocols should be administered for best possible muscle stimulation.

PRACTICAL APPLICATIONS

The results of this study indicate the potential of a whole-body vibration platform with a cable-pulley resistance system to stimulate the muscle activity of some arm muscles. Our subjects performed commonly used exercise as biceps curl which resulted in a significant increase in arm muscle activity during vibration stimulation. Coaches and practitioners should know that the specific whole-body vibration parameters used in the present study seem safe and suitable for the specific arm exercises when accounting for the total acceptable duration and combining exercises into a training program. Moreover, we found no evidence for dangerous accelerations in any of the studied body points. For the exercises tested in the present study, the commercially available platform with a cable-pulley resistance system can be used on a daily basis for 172 minutes when the studied exercises are performed. The results of the study show involuntary increase in EMG activity in arm muscles only during dynamic and static biceps curl exercises. The vibration signal delivered by the platform through the cables seems insufficient to induce additional EMG activation when dynamic triceps curl and lateral raise exercises are performed.

Acknowledgments

Authors state that they have no conflicts of interest. The work was not funded by NIH, Welcome Trust, HHMI, or any other. The present work will not benefit any companies or manufactures. Grant supports FWO-G0488-08 and FWO KN 1.5.017.08.

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CHAPTER 3

Effects of intensive whole-body vibration training on muscle strength and balance in adults with chronic stroke: A randomized controlled pilot study

Arch Phys Med Rehab 95(3): 439–446, 2014

Ekaterina Tankisheva [1]
An Bogaerts [2]
Steven Boonen† [3]
Hilde Feys [1]
Sabine M.P. Verschueren [1]

[1] KU Leuven – University of Leuven, Department of Rehabilitation Science
[2] KU Leuven – University of Leuven, Exercise Physiology Research Group
[3] KU Leuven – University of Leuven, Department of Experimental Medicine, Division of Gerontology and Geriatrics

ABSTRACT

Objectives: To investigate the effects of a 6-week whole-body vibration (WBV) training program in patients with chronic stroke.

Design: Randomized controlled pilot trial with 6 weeks follow-up.

Setting: University hospital.

Participants: Fifteen adults with chronic stroke were randomly assigned to an intervention (n=7) or a control group (n=8).

Interventions: Supervised intensive WBV training. The vibration group performed a variety of static and dynamic squat exercises on a vibration platform with vibration amplitudes of 1.7 and 2.5 mm and frequencies of 35 and 40 Hz. The vibration lasted 30 to 60 seconds, with 5 to 17 repetitions per exercise 3 times weekly for 6 weeks. The participants of the control group continued their usual activities and were not involved in any additional training program.

Main Outcome Measures: The primary outcome variable was the isometric and isokinetic muscle strength of quadriceps (isokinetic dynamometer). Additionally, hamstrings muscle strength, static and dynamic postural control (dynamic posturography) and muscle spasticity (Ashworth scale) were assessed.

Results: Compliance with the vibration intervention was excellent and the participants completed all 18 training sessions. Both vibration frequencies of 35Hz and 40Hz were well-tolerated by the patients and no adverse effects due to the vibration were noted. Overall, the effect of intensive whole-body vibration intervention resulted in significant between-group differences in favour of the vibration group only in isometric knee extension strength (knee angle 60°) (P=.022) after 6 weeks of intervention and in isokinetic knee extension strength (velocity of 240°/s) after a 6 weeks follow-up period (P=.005), both for the paretic leg.

Postural control improved after 6 weeks of vibration in the intervention group when the patients had normal vision and a sway referenced support surface (P<.05). Muscle spasticity was not affected by vibration (P>.05).

Conclusion: These preliminary results suggest that intensive WBV might potentially be a safe and feasible way to increase some aspect of lower limb muscle strength and postural control in adults with chronic stroke. Further studies should focus on evaluating how the

training protocol should be administered for best possible outcome and this compared against other interventions.

Key Words: rehabilitation; stroke; vibration; exercise.

List of abbreviations

CON Control

ES Equilibrium score

FAC Functional ambulation classification

SOT Sensory organization test

WBV Whole-body vibration

Stroke remains the leading cause of adult disability[1] with motor deficits and physical impairments including muscle weakness, loss of mobility, muscle spasticity and balance problems.[2] These impairments may promote a sedentary lifestyle and contribute to secondary complications like bone loss and fracture risk.[3] Muscle weakness results in low muscle forces and thus, a deficit of motor control and movement initiations.[4] Balance problems increase the risk of falls in older adults with stroke.[5] Long-term survivors with stroke also demonstrate long-standing dissatisfaction due to the activity limitation.[6]

Although functional recovery occurs mostly in the first 3 months following stroke,[7] previous research shows that the physical impairments are (partially) reversible with appropriate training. Exercise interventions are now recognized as a useful strategy to improve balance as well as mobility and muscle strength, and enhance functional independence in long-term survivors with stroke.[8-12] Those exercise programs commonly include exercise therapy, neuromuscular electrical stimulation, ergometer training, and training on mechanical devices such as balance trainers.[12-16]

Most of these trainings programs have addressed only one (or two) of the impaired domains, e.g. either strength or balance. Whole-body vibration (WBV), a recently developed method of neuromuscular training, might be a useful multidimensional approach to counter several of the impairments of patients with stroke. Previous research has shown that WBV training is a useful method to improve muscle strength and postural control in several populations, including sedentary adults[17,18] and elderly.[19-22] These promising findings suggest the possibility that vibration intervention might be a beneficial training therapy for patients with neurologic diseases. However, the effects of WBV training in persons with different neurological diseases including stroke are limited. Only a few studies have evaluated the effect of vibration training on patients with chronic stroke.[23-25]

One randomized controlled pilot study found no effects of 6-weeks vibration training (amplitude 3.75 mm and frequency 25 Hz) on muscle strength, muscle tone and gait performance.[23] The participants performed maximum 12 static knee squats, twice a week.

In another study, no effects after 6 weeks (5/weekly, less than 4 minutes vibration) of WBV intervention (30 Hz, 3 mm) were found on functional tests like the Berg Balance Scale or the Barthel Index.[25] In a study of Lau et al.,[24] vibration intervention (20 – 30 Hz, 0.44 – 0.6 mm) had no additional effect on neuromotor performance and incidence of falls in adults with chronic stroke compared to controls who performed the same exercises but with no vibration. Possible explanations for the different findings in those studies could be that the intensity of the vibration program was too low (e.g. only 4 minutes vibration/session) and/or that vibration excitation patterns (amplitude or frequency) could not produce a therapeutic effect. Additionally, the exercises performed on the platform might not have been challenging enough (static exercises). Therefore, the aim of the current pilot study was to explore the feasibility, safety and possible benefits of 6 weeks of more intensive WBV training in patients with chronic stroke in comparison to a control group.

Potential effects on knee muscular strength and muscle spasticity were assessed as well as static and dynamic balance and clinical measures of functional performance including a standard clinical neurological examination, Barthel Index, functional ambulation classification and a Brunström-Fugl-Meyer test. Our objective was to obtain preliminary evidence that would allow the design of a larger randomized controlled study.

METHODS

Participants and sample size

The study was designed as a randomized controlled pilot trial for patients with chronic stroke who had been admitted to the stroke rehabilitation unit of the University Hospitals Leuven. The inclusion criteria were: (1) age between 40 and 75, (2) first-ever stroke more than 6 months ago, (3) medically stable, (4) ability to stand independently with or without aids for at least 20 minutes, (5) ability to perform the experimental treatment independently. Patients were excluded if they met any of the following criteria: acute thrombotic diseases, severe heart and vascular diseases, pace-maker, acute hernia, diabetes and tumors or other neurological disorders like Parkinson's disease, multiple sclerosis, epilepsy and peripheral neuropathy, migraine. Patients suffering from rheumatoid arthritis, arthrosis, osteoarthritis, discopathy or spondylosis, were also not allowed to participate in the study.

Ethics

All participants gave written informed consent after receiving both verbal and written information about the study and its possible risks. The study was approved by the Leuven University Human Ethics Committee according to the declaration of Helsinki.

Recruitment and Randomization

The participants were recruited from a physical rehabilitation center in a university hospital. Thirty participants were contacted and underwent medical examination. Seventeen met the inclusion criteria and agreed to participate in the study. Two of the patients refused to continue the study after the first isometric knee muscle strength test before the randomization. In total, 15 participants were included in the study (see Fig 1).

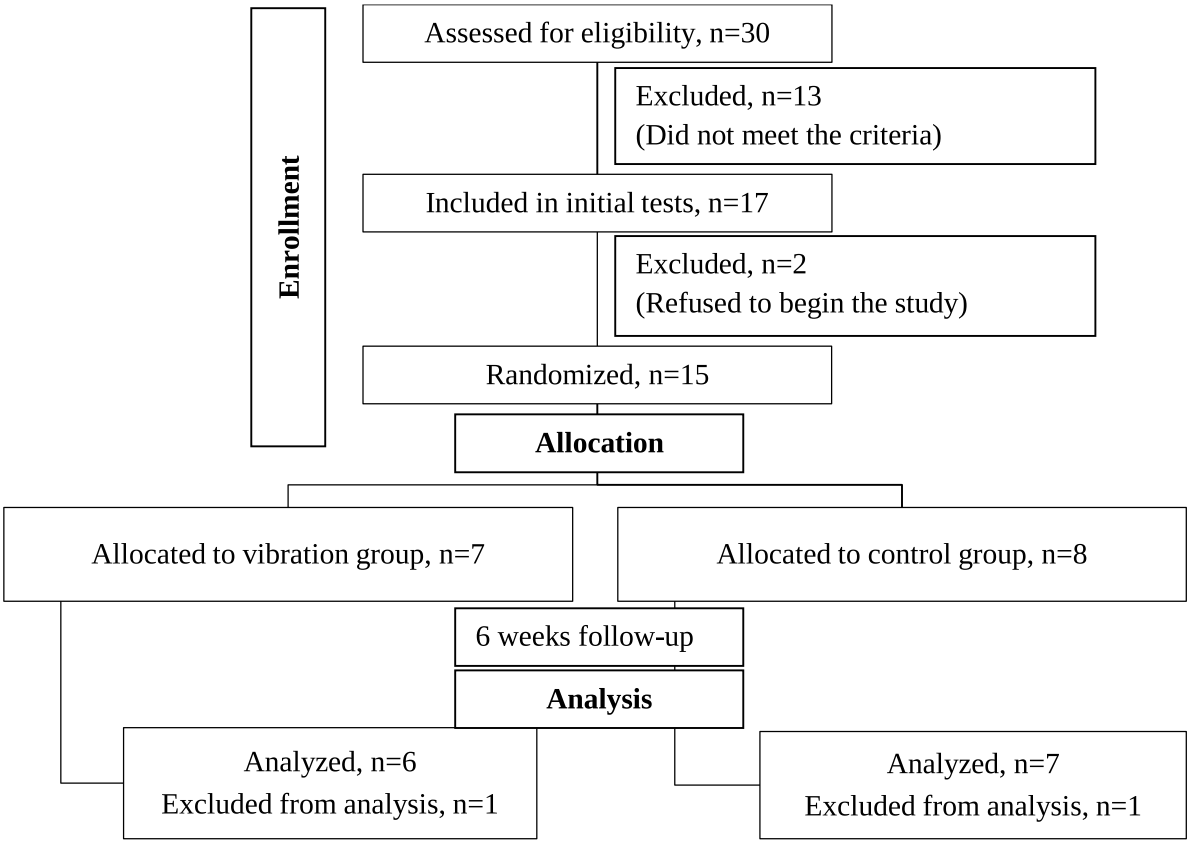

Figure 1. Flow chart of the participants.

The isometric quadriceps strength in a knee joint angle of 60° of all patients was measured before randomization. Participants were labeled as having “high” or “low” scores based on a cutoff value of 92Nm, and were then randomly assigned to a CON group and a vibration group, using computer-generated random number and concealed allocation.

Intervention

The patients of the intervention group (n = 7) participated in a training program on a vertical vibration platform (Powerplate[a]) 3 times a week for 6 weeks with a minimum 1 day of rest between the training sessions. Patients performed the following exercises: standing on their toes, knee flexion of 50 – 60° (high squat), knee flexion of 90° (deep squat), wide stance squat and one-legged squat. The training program was based on a program designed for elderly and previously successfully used.[22] Training intensity increased progressively by increasing the frequency (35 and 40 Hz) and/or the amplitude (1.7 and 2.5 mm) of the vibration signal. Vibration intensity gradually increased in the first 12 sessions and was more intensive in the last 6 sessions. Training volume rose systematically by increasing the duration of one exercise from 30 to 60 seconds, the number of sets of one exercise and/or the number of different exercises. Exercises in symmetric posture as well as weight bearing exercises to the paretic side were performed. One session had a maximal duration of 30 minutes and the applied vibration reached 19 minutes in the last weeks of the training program. All patients could walk with or without a walking aid and were capable to stand on the platform. Ankle-foot orthoses (worn by 2 subjects) were taken off during training and measurements. All participants were allowed to have a contact with the rails of the platform to support their balance especially during the dynamic exercises. All training sessions were supervised by a trainer who stood always beside the patients to assure their safety.

The participants of the control group were not involved in any additional training program and were asked not to change their lifestyle.

After the training period, there was a follow-up period of 6 weeks.

All outcome measurements were performed by an evaluator who was responsible for the instructions to the patients and who was not aware of patients’ group allocation. The evaluator was supervised by a senior trainer who was responsible for proper data acquisition and to supervise all training sessions. For practical reasons, it was not possible to have the senior trainer blinded for group allocation as there was no extra senior evaluator available who was not involved in the training program.

Descriptive measures

A standard clinical neurological examination assessed hemianopia, visual and tactile inattention and aphasia. Both the superficial touch and the deep sensibility (position sense, movement sense and vibration sense) were evaluated according to the guidelines described by Bickerstaff.[26] The Barthel Index determined the patient's degree of independence.[27] The functional ambulation classification (FAC) was used to evaluate functional (in)dependence of walking and distinguishes 6 levels of walking ability based on the amount of physical support required.[28] The Brunström-Fugl-Meyer test was used to measure sensorimotor impairment. It includes upper and lower extremity sensation, balance and motor control assessment.[28] To evaluate safety, compliance, and feasibility, all patients were encouraged to report possible (side) effects and to describe their feelings of perceived exertion during each training session by using the Borg's category ratio of perceived exertion scale (RPE).[29]

Outcome measures

All participants were tested at baseline, after the intervention period of 6 weeks, and after 6 weeks follow-up, respectively.

Muscle tone

Muscle spasticity of gastrocnemius, soleus, quadriceps, hamstrings, adductors and psoas muscles was measured with the Ashworth Scale.[30] Ashworth scale ranges between 0 and 4. The full score was the summation of the individual muscle scores, with a maximum of 24 points. The Ashworth scale has been shown to be reliable and reproducible method of measuring spasticity.[30]

Muscle strength

The knee extension and flexion muscle strength tests were performed on both the paretic and non-paretic legs with an isokinetic dynamometer (Biodex System[b]). The maximal voluntary isometric torque (Nm) of the quadriceps and hamstrings at a knee angle of 60° was measured. Additionally, isokinetic knee extension-flexion tests against lever arm of the dynamometer were performed at an angular velocity of 60°/s and 240°/s. All muscle strength measurements were previously shown to be reliable in adults with chronic stroke[23,31]

Postural control

Postural control was evaluated by using a computerized dynamic posturography platform (Equitest, Neurocom[c]). More specific, the Sensory Organization Test (SOT) was used to measure the ability to maintain postural control via visual, vestibular and proprioceptive information, according to a previously described testing protocol[32] SOT analysis provides equilibrium scores (ES) (%) which reflect how much the subject swayed in anterior-posterior direction. A mean ES of three trials per condition was used for the analysis. High ES indicated smaller sways and zero indicated a fall.

Data analysis

Mann-Whitney U tests were used to compare the baseline characteristics of the WBV and CON groups. A Shapiro–Wilk W test was used to assess the distribution for muscle strength, postural control and muscle tone. Due to the small sample size, differences in muscle strength, postural control and muscle tone between the WBV and CON group were tested with nonparametric Mann-Whitney U tests, multiple comparisons. Additionally, the Cohen d effect size was calculated based on means and SD. For Cohen's d an effect size below 0.3 is considered as "small" effect, around 0.5 as "medium" effect and 0.8 to infinity as "large" effect. For this pilot study no correction of the p-value for multiple testing was applied due to the exploratory nature of the study. The significance levels for all analyses were set to $P<.05$. All analyses were executed using the statistical package STATISTICA[d].

RESULTS

Participants

The baseline characteristics of the two groups are presented in table 1. No differences were observed in the Barthel Index, functional ambulation classification (FAC) and the Brunström-Fugl-Meyer between WBV and CON group before the intervention ($P>.05$). The maximum score (full independence) on the FAC was achieved in 9 subjects. The results of the functional ambulation classification (FAC) showed that 4 patients could walk without use of a walking aid and were ambulatory-independent only on a level surface. One patient was ambulatory-dependent with supervision without use of a walking aid and ambulatory-independent only on a level surface when a walking aid was used. One patient was in a wheelchair but was able to walk ambulatory-dependent with supervision without use of a walking aid. All other patients could walk ambulatory-independent without a walking aid.

Table 1. Subjects' characteristics at baseline and differences between groups.

Patients characteristics	WBV	CON	Difference
Sex, men/women (n)	4/3 (n = 7)	6/2 (n = 8)	
Age (years) (mean ± SD)	57.4 ± 13	65.3 ±3.7	P = .13
Type of stroke			
• Left/ Right hemisphere	4/3	4/4	
• Ischemic/ Hemorrhagic lesions	6/1	5/3	
Years after stroke (mean ± SD)	7.71 ±8.6	5.28 ±3.6	P = .50
Isometric knee extension strength 60°, Nm			
• Paretic leg (mean ± SD)	102.9 ±15.8	90.8 (±22.4)	P = .49
• Nonparetic leg (mean ± SD)	141.1 ±13.4	130.9 ±17.9	P = .24
Descriptive measurements			
• Clinical neurological examination			
• disturbed superficial and deep sensibility (n)	1	3	
• reduced hemianopia (n)	1	2	
• speech problems (n)	1	2	
• Barthel index (mean ± SD)	95 ± 7.1	86.3 ± 12.2	P = .12
• Functional ambulation classification (median/range)	5 (4 - 5)	5 (3 - 5)	P = .81
• dependent for supervision (n)	0	2	
• independent, level surface only (n)	2	1	
• independent (n)	5	4	
• Brunström-Fugl-Meyer test (mean ± SD)	25 ± 2.9	21.1 ± 6.7	P = .18

NOTE. Values are n, mean ± SD, median (range), or as otherwise indicated. Abbreviations: F, female; M, male.

One participant in the intervention group refused to repeat the tests after the follow-up. One participant in CON did not perform the follow-up tests because of an injury unrelated to the study.

Effect of the intervention

Compliance with the vibration intervention was excellent (100%) and the participants completed all training sessions. All patients tolerated both vibration frequencies of 35 Hz and 40 Hz and they did not consider the exercises as too difficult. On average, the patients reported a score of 3 on the Borg's scale indicating a moderate degree of exertion. Only 1 person indicated a Borg's score of 6 (heavy). No adverse effects due to vibration were reported, although, some of the participants described some itching in the legs after the first vibration sessions but this phenomenon resolved spontaneously. None of the subjects felt any dizziness or fatigue during the vibration training.

Muscle tone

The results of the Ashworth scale (muscle tone) showed no significant differences between the two groups at baseline, after 6 weeks vibration, and 6 weeks follow-up (P>.05). The WBV intervention did not affect the level of muscle spasticity (table 2).

Table 2. Muscle tone and knee muscle strength at baseline, after 6 weeks WBV, and after 6 weeks' follow-up

NOTE. Values are median (minimum-maximum) or mean ± SD.

Outcome measures	Before WBV		After WBV		Follow-up	
	WBV	CON	WBV	CON	WBV	CON
Muscle tone (Ashworth Scale, points)	4.0 (0-9)	5.0 (0-14)	3.0 (0-5)	5.0 (0-10)	3.0 (0-9)	2.0 (0-11)
Muscle strength						
Isometric knee extension 60°, Nm						
Paretic leg	102.9±15.8	90.8±22.4	**120.5±9.2*‡**	87±23.1	114.9±13.3	87.2±25.1
Nonparetic leg	141.1±13.4	130.9±17.9	156.2±15.3	124.2±22.2	148±12.6	129.1±25.7
Isometric knee flexion 60°, Nm						
Paretic leg	41.4±15	30.5±27.2	46±16.9	36.8±26.6	44±16.2	35.2±25.7
Nonparetic leg	83.4±24.5	74±25.3	81.5±20.5	72.4±23	77.1±18.5	71.9±24.5
Isokinetic knee extension 240°/s, Nm						
Paretic leg	43.1±10.1	44.7±12.1	50.2±9.3	41.4±10.6	**48.1±7.9*‡**	**39.2±9.3†**
Nonparetic leg	61.7±8.3	59.6±14.2	67.3±7.8	60.6±11	67±12.1	59.4±13
Isokinetic knee flexion 240°/s, Nm						
Paretic leg	25.3±4.9	27.1±13	**28.3±3.4***	23.7±10.3	29.6±6.4	24.4±12.3
Nonparetic leg	52.4±11.8	51.7±14.7	57.8±10.2	54.5±15.6	58±11.2	49.5±14.6
Isokinetic knee extension 60°/s, Nm						
Paretic leg	68.7±25.3	65.4±16.3	82.9±22.2	62.5±18.6	77.7±21.1	63.2±18
Nonparetic leg	111.7±14.6	98.1±23.3	125±11.7	104.3±20.5	125.3±14.7	110.3±20
Isokinetic knee flexion 60°/s, Nm						
Paretic leg	27.3±13.7	20.9±15.3	32.5±15	24.6±15.7	30.3±13.3	20.3±12.4
Nonparetic leg	54.7±14.5	53.6±18	60.6±5	56.7±17.9	64.1±11.5	56.1±21.4

* Within-group difference: a significant increase compared with baseline.
† Within-group difference: a significant decrease compared with baseline.
‡ Between-group difference: a higher muscle response in WBV group compared with CON group.

Muscle strength

Between-group and within-group differences on muscle strength before and after the intervention and at 6 weeks follow-up are presented in Table 2. No significant differences in knee muscle strength were found between both groups at baseline for both legs (P>.05).

Significant between-group differences were found in favour of the vibration group only in isometric knee extension strength (knee angle 60°) (P=.022) after 6 weeks of intervention and in isokinetic knee extension strength (velocity of 240°/s) after 6 week follow-up period (P=.005), both for the paretic leg. The effect size based on between-group differences is presented in figure 2. The Cohen's d effect size for isometric (knee angle 60°) and isokinetic (velocity 60°/s) flexion muscle strength appeared small to medium. The effect size of the intervention for isometric extension strength (knee angle 60°) was 1.52 and for isokinetic extension muscle strength (velocity 240°/s) was 1.77.

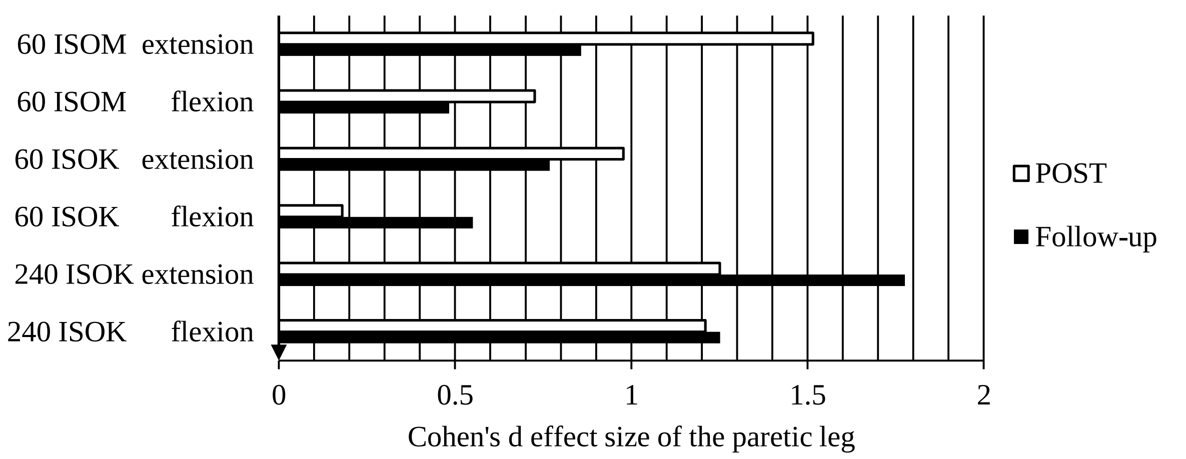

Figure 2. Effect of the intervention presented as Cohen's d effect size. The effect size is based on between-group differences of the paretic leg. An effect size below 0.3 is considered as "small" effect, around 0.5 as "medium" effect and 0.8 to infinity as "large" effect. NOTE: ISOM – isometric knee muscle strength; ISOK – isokinetic knee muscle strength.

No differences between WBV and CON were found for the non-paretic leg. Significant within-group differences were found in the vibration group. Isometric knee extension strength (knee angle 60°) of the paretic leg increased significantly after the intervention (+18.7%, P=.046) and was maintained after 6-week follow-up. No changes in isometric knee strength of the paretic leg were found in the CON group (P>.05).

No changes in isokinetic knee muscle strength (velocity of 60°/s) of the paretic leg were found in either WBV or CON group after 6-week WBV and 6-week follow-up (P>.05).

No significant change in isokinetic knee extension strength (velocity of 240°/s) of the paretic leg was found after the vibration training (+20.3%, P=.051). At follow-up the increase did reach significance (+14.1%, P=.046). The isokinetic knee extension strength (velocity of 240°/s) of the paretic leg in the control group remained the same (-5.17%, P>.05) after the first 6 weeks and decreased significantly after the follow-up (-10.2%, P=.042).

A significant increase in isokinetic knee flexion strength (velocity 240°/s) of the paretic leg (+13.9%, P<.046) was found in the WBV group after six weeks of training. No changes in isokinetic knee flexion strength (velocity of 240°/s) of any of the paretic leg were found in the CON group (P>.05).

No changes in isometric or isokinetic knee strength of non-paretic leg were found in either WBV or CON group (P>.05).

Postural control

Table 3 shows the results on balance in Sensory Organisation Test (SOT). The participants in both groups swayed more with increasing difficulty of the test condition (declining equilibrium scores (ES) from C1 to C6 when data from all groups were combined, *P*<.05). No difference was found between WBV and CON group at baseline for any condition. The ES increased significantly after the vibration training only in condition 4 – normal vision and sway referenced support surface (P<.05, effect size=1.47). The increase was maintained after the follow-up. No significant changes in ES were detected in the control group (P>.05).

Table 3. Sensory Organization Test (SOT)

	WBV group			Control group		
	PRE	POST	Follow-up	PRE	POST	Follow-up
C1	93.7 ± 0.8	92.7 ± 2.3	93.4 ± 2.4	91.9 ± 3.2	92.6 ± 3	91.4 ± 1.9
C2	90.9 ± 2.8	91.5 ± 2.7	92 ± 2.9	89.1 ± 3.2	86.2 ± 4.2	88.6 ± 2.5
C3	90.3 ± 4.5	91.6 ± 1.9	92.5 ± 2.9	88.7 ± 3.7	88.9 ± 4.3	88.3 ± 4.4
C4	72.7 ± 7.8	82.8 ± 4.5*	82.2 ± 6.3	74.8 ± 5.1	79.1 ± 6.8	81 ± 5.6
C5	46.3 ± 29.6	50.5 ± 21.3	59 ± 24.5	37.9 ± 28.2	41.3 ± 30.2	57.1 ± 13
C6	55.3 ± 12.6	64.2 ± 8.4	68.2 ± 7.9	47.8 ± 23.9	53.1 ± 24.6	48.5 ± 23.6

NOTE. SOT equilibrium score (%) presented as mean ± SD for the intervention and CON group at baseline (Pre), after 6 weeks (Post), and after 12 weeks (Follow-up). Abbreviations: C1, normal vision and normal support surface; C2, eyes closed and normal support surface; C3, sway-referenced vision and normal support surface; C4, normal vision and sway-referenced support surface; C5, eyes closed and sway-referenced support surface; C6, sway-referenced vision and sway-referenced support surface.

DISCUSSION

The current pilot study suggests that a specific vibration program can have potential beneficial effects on some aspects of knee muscle strength and balance control in patients with chronic stroke. All participants completed the intervention successfully and compliance was excellent. No adverse effects due to vibration were reported and the increase in training intensity was well tolerated. All participants expressed their willingness to perform different exercises on a vibration platform for even longer periods, suggesting that vibration training may be a feasible training program for patients with chronic stroke.

The main findings of the present randomized controlled pilot study are that patients with chronic stroke improved some aspects of knee muscle strength and postural control after 6 weeks of whole-body intervention. The standardized Cohen *d* effect size (figure 2) reflected a small to large mean effect as a result of the vibration intervention. This supports the likelihood of a clinically meaningful effect in a larger randomized controlled trial. Although all participants in both groups continued to be involved in their conventional training, knee muscle strength tended to decrease in the control group, providing further evidence for the additional role of whole-body vibration in improving lower limb muscle strength.

Brogårdh et al.[23] did not find an improvement in isometric or isokinetic knee muscle strength after 6 weeks of whole-body vibration. However, we used a different protocol with patients performing different dynamic exercises (also one-legged exercise), 3 times weekly between 5.5 to 19 minutes whereas Brogårdh et al. only used static squats twice weekly for a maximum of 12 minutes. Also, the vibration parameters (3.75 mm, 25 Hz) used their study differed from those in the present study (1.75 and 2.5 mm, 35 and 40 Hz). In this regard, the muscle loading in the study by Brogårdh et al. may have been insufficient to result in neuromuscular adaptation. Similarly, a study by Lau et al.[24] failed to show a difference in isometric knee muscle strength between the vibration and the control group after 8 weeks whole-body vibration. The possible reason might have been that the participants in the control group performed the same exercises but without vibration. Moreover, the intensity of the vibration excitation patterns with very low loading (0.44 – 0.60 mm) used in their study may have been insufficient to induce a tonic vibration reflex and thus, to provoke further training effects in patients with stroke.

In the present study, postural control (equilibrium score) did not change significantly when the support surface remained stable (condition 1 – 3), most probably because the tests were not challenging enough for the patients. However, postural control improved significantly in the vibration group when the visual information was normal and the support surface was disturbed (condition 4). The improvement in postural control in this condition where ankle propioception input is disturbed might be related to the improvements in muscle strength and propioception after vibration training. It should be taken into account that the patients were allowed to have a contact with the handrails during the training when they felt unstable especially while performing dynamic exercises. Therefore, the results should be interpreted with caution as the effect on the postural control could be minimized because the training might have not been challenging enough.

Even, some improvements in knee muscle strength and postural control were found, clear recommendations concerning the optimal vibration excitation patterns (amplitude, frequency and duration of the vibration signal) cannot still be provided. Therefore, further randomized controlled trials are recommended to provide more insight on how to optimize the vibration protocols for patients with stroke.

Based on the Cohen's d effect size of the isometric knee extension strength of 60°, the effect size of 1.52 (r= 0.60) was used to calculate the minimum sample size required for a future randomized controlled trial. Based on a two-tailed alpha level of 0.05 and power of 95%, the minimum required total sample size will be 40 participants divided in two groups – a vibration group (n=20) and a control group (n=20).

Study limitations

Our study has several limitations and the results should be interpreted in the context of its design. First, our sample size was small, and we acknowledge that this was an exploratory pilot study and the formal sample size was not calculated due to the pilot nature of the study. A larger randomized controlled trial is needed to further investigate the possible positive effects of vibration on patients with stroke. Second, it cannot be excluded that the improvement of knee muscle strength and postural control can be a result of the different dynamic exercises performed on the platform. It would have been interesting to include patients in a resistance training group to perform the same exercises on the platform but without vibration (placebo group). Third, the participants and the trainer were not blinded to the group allocation which was difficult to achieve due to the nature of the study. The trainer supervised all training sessions and all measurements. However, all efforts were made to standardize the measurements to minimize the possible bias. Finally, our preliminary findings should not be generalized to the overall patients with stroke. Most of patients in the present study were ambulatory-independent with or without a walking aid and had mild to moderate physical impairments and thus, are not representative sample of patients with severe impairments after stroke. Moreover, the patients in our study were only adults with chronic stroke and thus, the results cannot be referred to patients with acute stroke. The possible effect of vibration intervention on patients with severe impairments or patients with acute stroke requires further investigation.

CONCLUSIONS

The results of this randomized controlled pilot trial suggest that intensive WBV training may be a safe and feasible training program in patients with chronic stroke. Our preliminary results suggest some improvements in lower limb muscle strength and postural control after 6 weeks of training. Further studies should focus on evaluating how the training protocol should be administered for best possible outcome.

Suppliers' list:

a. Power Plate Acquisitions, LLC., 160 Jan van Gentstraat, 1171GP, Badhoevedorp, The Netherlands
b. Biodex Medical Systems Inc, 20 Ramsay Road, Shirley, New York, 11967-4704.
c. Equitest, Neurocom, 9570 SE Lawnfield Road, Clackamas, OR 97015, USA
d. STATISTICA, Version 9, 2300 East 14th Street Tulsa, OK 74104, USA

Acknowledgments

Supported by the Research Foundation Flanders (FWO), Brussels, Belgium (project nos. FWO-G0488-08, FWO-KN-1.5.017.08). No commercial party having a direct financial interest in the results of the research supporting this article has conferred or will confer a benefit on the authors or on any organization with which the authors are associated.

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CHAPTER 4

Effects of a 6-month local vibration training on bone density, muscle strength, muscle mass and physical performance in postmenopausal women

(Submitted to JSCR)

Ekaterina Tankisheva [1]
An Bogaerts [2]
Steven Boonen† [3]
Christophe Delecluse [2]
Paul Jansen [4]
Sabine M.P. Verschueren [1]

[1] KU Leuven – University of Leuven, Department of Rehabilitation Science, Musculoskeletal Rehabilitation Research Centre
[2] KU Leuven – University of Leuven, Department of Biomedical Kinesiology, Research Centre for Exercise and Health
[3] KU Leuven – University of Leuven, UZ Leuven, Department of Experimental Medicine
[4] Thomas More, Campus Geel, Life Sciences, Mobilab, Geel, Belgium

ABSTRACT

Objectives: To investigate the effect of 6 months local vibration training on bone mineral density, muscle strength, muscle mass and physical performance in postmenopausal women (66 – 88 y).

Design: Randomized controlled pilot trial.

Setting: Daily care service flats and rest homes.

Participants: Thirty-five postmenopausal women were randomly assigned to a vibration (n = 17) and a control group (n = 18).

Interventions: Supervised local vibration training. The vibration group received 6-month local vibration treatment with frequency between 30 and 45 Hz and acceleration between 1.71 and 3.58 *g*. The vibration was applied on the mid-thigh and around the hip in supine lying position once per day, 5 days/week. The participants of the control group continued their usual activities and were not involved in any additional training program.

Main Outcome Measures: The primary outcome variables were the bone mineral density of the hip, and isometric and dynamic quadriceps muscle strength. We assessed the muscle mass of the quadriceps and physical performance. Additionally, the feasibility, side effects and compliance were evaluated after 6 months of local vibration training.

Results: Overall, the results showed a net benefit of 13.84% in isometric muscle strength at 60° knee-angle in favor of the vibration group compared to controls ($P<0.01$). No changes in bone mineral density, muscle mass or physical performance were found in both groups ($P>0.05$).

Conclusion: 6 months of local vibration training improved some aspects of muscle strength, but had no effect on bone mineral density, muscle mass and physical performance in postmenopausal women. The specific vibration protocol used in the present study can be considered as safe and suitable for a local vibration training program. Compliance with the vibration intervention was excellent and the training protocol was well-tolerated by the participants. However, the subjects considered that 5 days/week training was too time-consuming.

Key words: local vibration, muscle, bone mineral density.

List of abbreviations

BMD Bone mineral density

CON Control

mPPT Physical performance test

SWT Shuttle walk test

WBV Whole-body vibration

Aging is associated with a decrease in bone mineral density (BMD) known as osteoporosis, and a decline of lean muscle mass and muscle strength known as sarcopenia.[1,2] Both osteoporosis and sarcopenia are important socio-economic and personal problems as they contribute to an increased fall risk, an increased number of hip and vertebral fractures, and physical weakness.[3-5] Hip fractures are associated with high mortality and morbidity rate among postmenopausal women.[6] Therefore, the prevention of bone loss and muscle weakness remains an important question.

Mechanical loading by means of physical exercise has been shown to have an osteogenic effect, to increase muscle strength and to improve body balance.[7-9] High-impact exercises such as running and jumping may enhance bone acquisition in young age,[10-12] and maintain bone mineral density, reduce the risk of falls and osteoporotic fractures at older ages.[13-18] However, high-impact training is not practical and even unsafe in a significant proportion of older individuals, potentially leading to injuries and even fractures.[19]

An alternative training method might be the vibration training which combines factors of both impact exercise and conventional resistance training. While effects of long-term whole-body vibration (WBV) training on BMD and muscle power have previously been reported,[20-23] little is still known about the possible benefits of locally applied vibration training. Local vibration training might be more adequate for a large segment of the adult's populations including frail elderly, adults that are in a wheelchair or bedridden individuals, and patients with knee osteoarthritis who are unable to stand on a whole-body vibration platforms. Moreover, applying the vibration training locally may avoid the significant decrease of vibration signal up to the thigh and the hip,[24] e.g. patients with knee prostheses. Delivering the vibration locally at the regions which are most at risk for fractures (hip and spine) or most in need of muscle strengthening might be a more suitable approach.

Therefore, we hypothesized that the specific local vibration training used in the current study would be a feasible and safe training method to improve bone density, muscle strength and muscle mass, and physical performance in postmenopausal women. As a result, a randomized controlled pilot study was conducted to evaluate the feasibility, safety and potential effectiveness of 6 months of locally applied vibration training in postmenopausal women.

METHODS

Participants

The study was designed as a randomized controlled trial for postmenopausal women who resided in long-term care settings. The inclusion criteria were: (1) age above 65, (2) free from medications known to affect bone metabolism or muscle strength, (3) obtained approval following an extensive medical examination by a general practitioner, and (4) free from hip prosthesis. Participants were excluded if they met any of the following criteria: severe heart and vascular diseases or neurological disorders like Parkinson’s disease, multiple sclerosis, epilepsy and peripheral neuropathy.

Recruitment and Randomization

Fifty postmenopausal women volunteered to participate and underwent an extensive medical screening and 35 of them met the inclusion and exclusion criteria and were included in the study. The participants were randomly assigned to a vibration group (n=17) or a control group (n=18) using computer-generated random numbers (Figure 1). None of the participants were engaged in another training program, or in regular organized sports or other physical activities.

Ethics

All participants gave written informed consent after receiving both verbal and written information about the study and its possible risks. The study was approved by the Leuven University Human Ethics Committee according to the declaration of Helsinki.

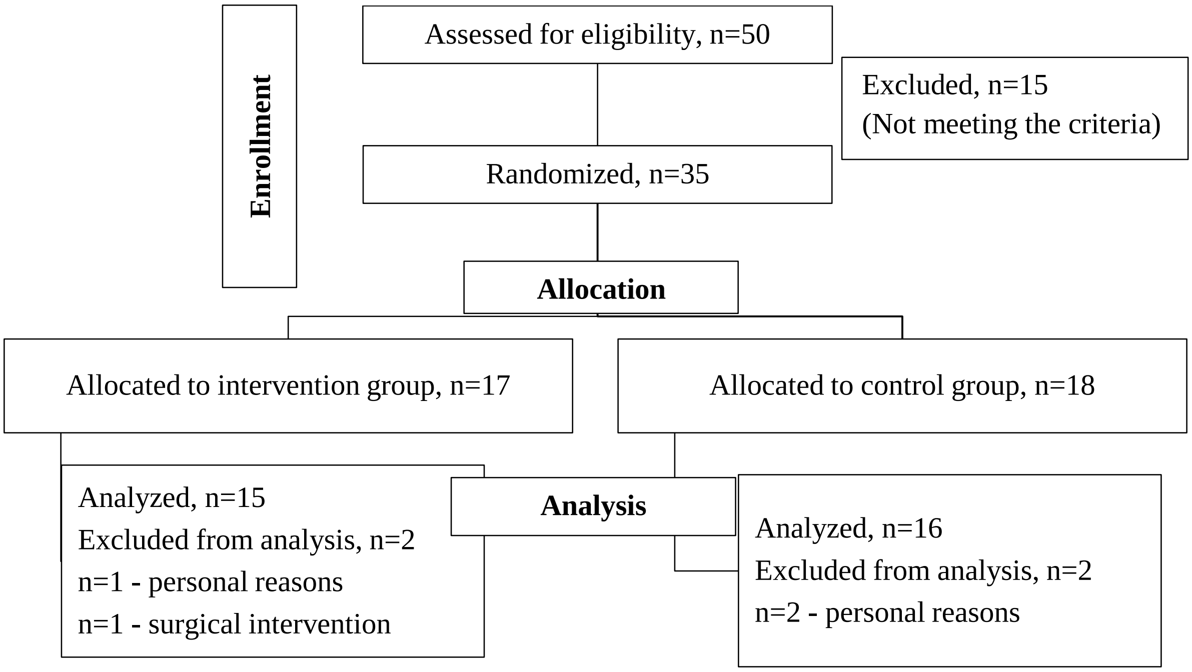


Figure 1. Flow chart of the participants.

Vibration equipment

Based on a finite element model analysis (Appendix 1), custom-made vibration devices were specially designed for the current study (Figure 2).

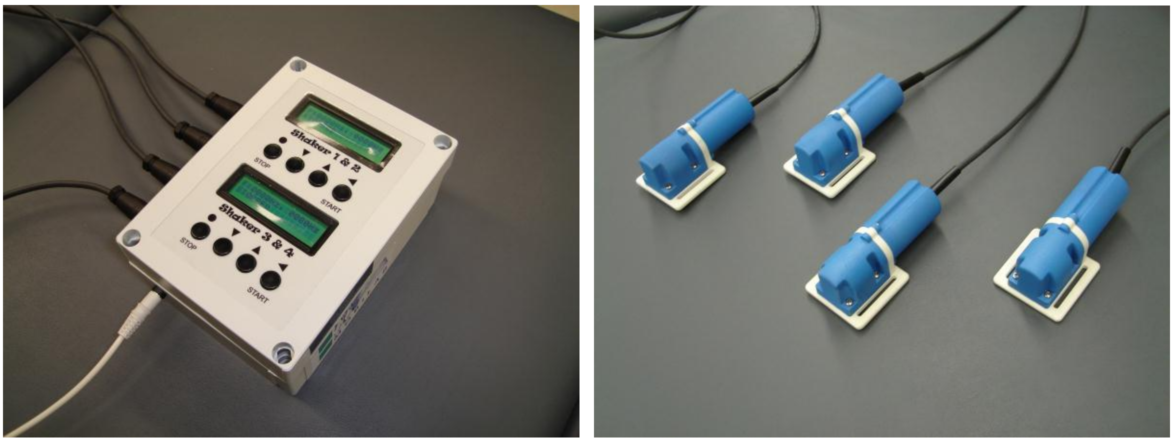


Figure 2. Control unit and vibrators.

Each device consisted of one control unit, four vibrators connected to the control unit and a medical approved power supplier (Powerbox, 24V – 2.9A[a]). Each vibrator had an encoder. The rotating element inside the vibrators was a cylindrical brass part with a diameter of 20 mm and a thickness of 8 mm (weight: 0.022 g). The frequency of the rotating element was continuously adjustable between 25 Hz and 45 Hz, which resulted in peak acceleration between 1.71 and 3.58 *g* as measured by accelerometer (MEMS, SMB380[b]). The frequency, the duration and the number of bouts as well as the duration of the rest periods were adjustable and displayed on the control unit. The vibrators were attached to the body by a strap. Because of the structure of the underlying limb, the centrifugal forces on the body were buffed (mass-spring system). The motor control of the vibrators ensured that the set vibration parameters remained constant independently of the applied buffing by the body.

Intervention

The participants were instructed how to apply the vibrators in supine lying position once per day, 5 days/weekly for a period of 6 months, at home. All participants applied the vibrators on the mid-thigh (m. quadriceps) and around the hip (m. gluteus maximus and m. gluteus medius) using bandages. The required vibration program was set up before each training period. After the end of the daily set-up training period, the vibration device stopped automatically. Every week one training session was supervised by a researcher to ensure that the training protocol was followed correctly. The compliance rate was recorded by the participant by using a calendar book.

During the 6-month vibration intervention period, training loading increased progressively according to the overload principle by increasing the duration and numbers of bouts and shortening the rest periods as well as increasing the acceleration and the frequency of the training (Table 1).

Table 1. Characteristics of the vibration training program

Period (week)	Intensity					Vibrators	
	Volume Duration (seconds)	Acceleration (g)	Frequency (Hz)	Bouts	Rest (seconds)	Thigh	Hip
1 → 2	30	1.71	30	4	60	1	1
3 → 6	60	2.94	35	5	60	1	1
7 → 11	60	3.4	40	5	30	1	1
12 → 16	60	3.4	40	5	30	2	1
17 → 21	60	3.58	45	7	30	2	1
22 → 26	60	3.58	45	8	30	2	1

The first 11 weeks, vibrators were applied on each side – 1 on the hip and 1 on the mid-thigh, respectively. From 12th week till the end of the 6-month period, 3 vibrators were applied on each side – 1 on the hip and 2 on the thigh, respectively to allow further increase of the training stimulus for the muscle. The vibrators were applied first on the right or left side and then on the other one. The duration of one session lasted for a maximum of 30 minutes.

The participants of the control group were not involved in any additional training program and were asked not to change their lifestyle.

Measurements

To evaluate safety, compliance, and feasibility, all subjects were encouraged to report possible (side) effects or occurrence of falls during each training session. At the end of the study, each participant filled in a questionnaire about the training protocol and the usage of the vibration device.

Bone mineral density, muscular strength and muscle mass, as well physical performance were assessed at baseline and at 6 months in both groups. The assessors for BMD and muscle mass were blind to the patients' allocation to both the experimental and the control group. For practical reasons, it was not possible to have an assessor for muscular strength, SWT and mPPT blinded for group allocation as there was no extra senior evaluator available who was not involved in the training program.

Bone mineral density

BMD of the right hip was assessed by DXA using the QDR- 4500A device (Hologic, Waltham[c]). Standard positioning was used with anterior–posterior scanning of the proximal femur. The CV for total hip DXA measurement in our laboratory is 0.56%.

Muscle strength

Muscle strength was recorded unilaterally on the right side on a motor-driven isokinetic dynamometer (Biodex System[d]) by means of a standard protocol of dynamic and isometric tests.[21]

Isometric strength: the participants performed a maximal voluntary muscle contraction of the knee extensors peak torque (Nm) was recorded. The knee joint angle was set at 30°, 60° and 90°.

Isokinetic strength: the participants performed a series of isokinetic flexion-extension movements against the lever arm of the dynamometer. The velocity was set at 60°/s, 180°/s and 240°/s. The knee extension was initiated at a joint angle of 90° and ended at 160°, and the peak torque was assessed (Nm).

Isotonic strength: the participants performed several ballistic tests with a resistance of 0%, 20% and 40%. The degree of resistance was individually determined as a percentage of the isometric maximum in the knee angle of 90°. The maximal velocity of the lever arm was recorded to determine the ballistic strength. The knee extension was initiated at a joint angle of 90° and ended at 160°. After each extension, the leg was passively returned to the starting position.

Muscle mass

Muscle mass of upper leg was assessed by multislice computed tomography (CT) scan (Siemens Sensation 16[e]) and the delivered axial slices of legs were analyzed with the program Volume. The test was previously described by our research group and the reliability was tested, which yielded an intraclass correlation coefficient of 0.99.[20] The summed muscle volume (in cubic centimetres) was analyzed. Measurements were performed in the University Hospital and were executed by an expert radiologist.

Physical performance

To evaluate the functional capacity, a modified physical performance test (mPPT) for elderly was performed. mPPT includes different timed or graded functional tests described previously.[25] Additionally to mPPT, physical fitness and endurance were assessed using the shuttle walk test (SWT) which is a standardized incremental field walking.[26]

Data analysis

Due to the small sample size, between- and within-group differences in muscle strength, muscle mass and bone mineral density were tested with nonparametric tests. Mann-Whitney U tests were used to compare the baseline characteristics of the vibration and the control groups. A Shapiro–Wilkinson W test was used to assess the distribution for muscle strength, muscle mass and bone mineral density. Additionally, the Cohen's d effect size was calculated based on means and SD. For Cohen's d an effect size below 0.3 is considered as "small" effect, around 0.5 as "medium" effect and 0.8 to infinity as "large" effect. The significance levels for all analyses were set to $P<0.05$. All analyses were executed using the statistical package STATISTICA[f].

RESULTS

Participants

The baseline characteristics of the two groups are presented in Table 2. The intervention group's average weight was 9 kg higher than the control group ($P<0.015$), and the body mass index (BMI) of the intervention group was 3 kg/m^2 higher compared with controls ($P<0.045$).

Two participants in the intervention group did not complete the full training protocol due to reasons unrelated to the training 1) personal reasons (dropped out after 6 weeks of vibration), and 2) surgical intervention (dropped out after 3 weeks of vibration). Two participants in the control group refused to repeat the tests after the 6 months period due to personal reasons. The average compliance with the vibration intervention was excellent (X: 96.5%). All participants tolerated the vibration protocol well and they did not consider the training as unpleasant. None of subjects reported any adverse effects due to vibration. However, in the questionnaires after the 6-month period, 80% of participants in the vibration group reported that applying the vibrators 5 days/weekly was time consuming and they did not show the willingness to participate in a vibration training program for a longer period.

Effect of the intervention

No significant differences were observed at baseline between the experimental and the control groups in terms of BMD, muscle strength, muscle mass, fat mass, or physical performance (Table 2).

Muscle strength

Significant between-group difference after the 6-month local vibration training was found in favor of the vibration group only in isometric knee extension strength of 60° with a net benefit of 13.84% ($P=0.01$). No between-group differences were found in the other isometric, isokinetic and isotonic muscle strength tests ($P>0.05$).

Table 2. Subjects characteristics at baseline and differences between groups.

Parameter	Vibration	Control	P-value
N	17	18	
Age (years)	75.7 (66–84)	77.6 (68–88)	0.39
Height (m)	1.58 (1.5–1.7)	1.57 (1.46–1.65)	0.45
Weight (kg)	73.4 (55– 93)	64.1 (41– 88)	0.015*
BMI (kg/m^2)	29.3 (20.9–36.2)	26.1 (17.1–34.2)	0.045*
Total hip BMD (g/cm^2)	0.834 ± 0.137	0.836 ± 0.114	0.83
Muscle mass (cm^3)	83.7 ± 10.8	79.4 ± 12.3	0.41
Fat mass (cm^3)	110.2 ± 26.6	98.6 ± 30.5	0.41
Isometric strength (Nm)			
• 30°	42.0 ± 11.0	48.8 ± 13.0	0.16
• 60°	91.2 ± 23.9	96.6 ± 20.7	0.24
• 90°	103.7 ± 24.6	105.0 ± 30.7	0.95
Isokinetic strength (Nm)			
• 60°/s–extension	87.3 ± 23.7	84.0 ± 22.4	0.98
• 60°/s–flexion	34.9 ± 12.6	35.0 ± ± 9.2	0.79
• 180°/s– extension	53.2 ± 13.2	50.5 ± 12.5	0.88
• 180°/s– flexion	30.0 ± 9.4	31.1 ± 7.9	0.75
• 240°/s– extension	50.7 ± 11.1	47.9 ± 12.4	0.72
• 240°/s– flexion	33.9 ± 8.3	35.7 ± 11.2	0.69
Isotonic strength			
• 0%	316.8 ± 35.1	319.8 ± 52.2	0.63
• 20%	243.7 ± 42.2	234.2 ± 41.3	0.72
• 40%	138.1 ± 47.0	130.7 ± 22.2	0.35
Physical performance			
• mPPT, points	33.5 (28–36)	32.5 (25–36)	0.35
• SWT, m	317.1 (180–469)	307.8 (188–447)	0.71

NOTE. Values are mean ± SD or ranges in the parentheses.
* Between-group difference: a significant difference between vibration and control groups

The effect size based on between-group differences is presented in figure 2. The Cohen's *d* effect size for isometric knee extension strength of 60° was large, + 1.02. The effect size of the intervention for the other isometric, isokinetic and isotonic tests appeared small to medium (0.1 – 0.8).

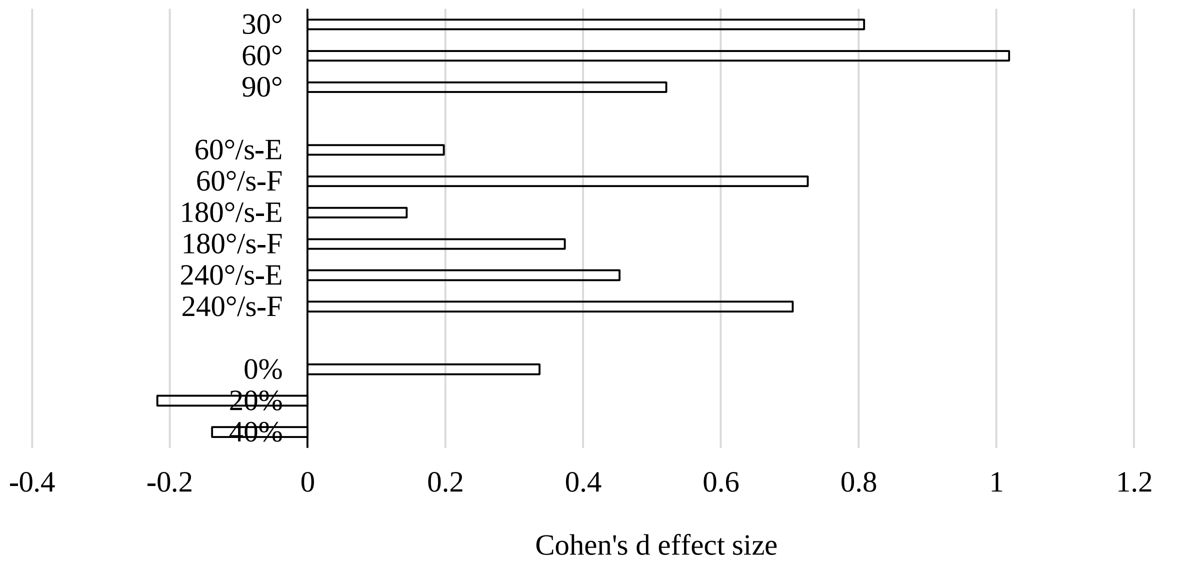
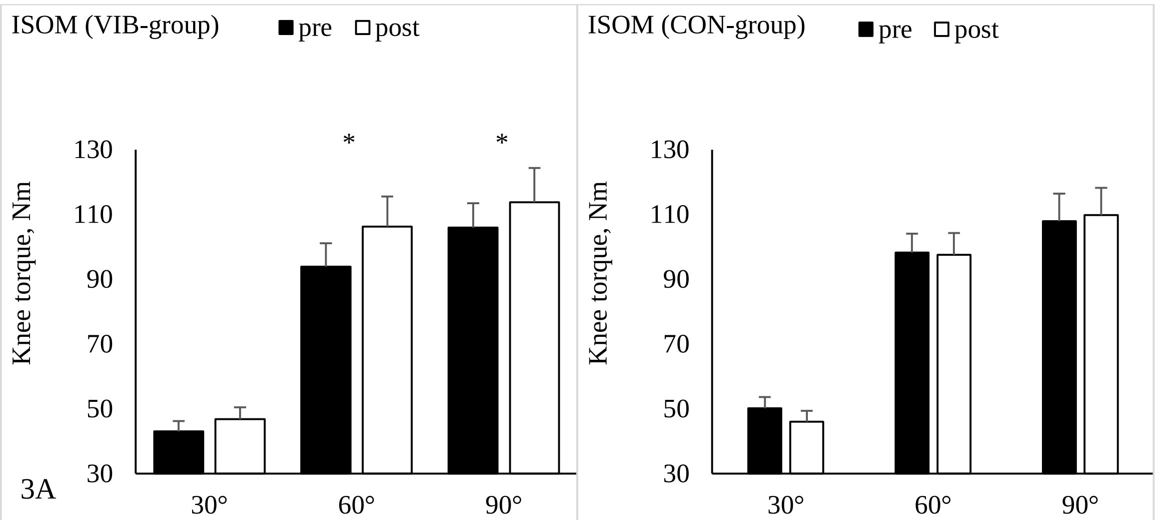


Figure 2. Effect of the intervention presented as Cohen's d effect size. The effect size is based on between-group differences. An effect size below 0.3 is considered as "small" effect, around 0.5 as "medium" effect and 0.8 to infinity as "large" effect. (E – extension, F – flexion)

Concerning the within-group differences, isometric strength of 60° and 90° of the knee extensors significantly increased by 12.88% and 6.61%, respectively, in the vibration group after the 6-month local vibration training (P<0.05, Figure 3A).



Isokinetic knee flexion strength of 60°/s and 180°/s changed significantly over time in the vibration group by 23.00% and 24.06%, respectively (P<0.05, Figure 3B). No within-group differences were found in the other isometric, isokinetic and isotonic muscle strength tests in either the vibration or the control group (P>.05, Figure 3).

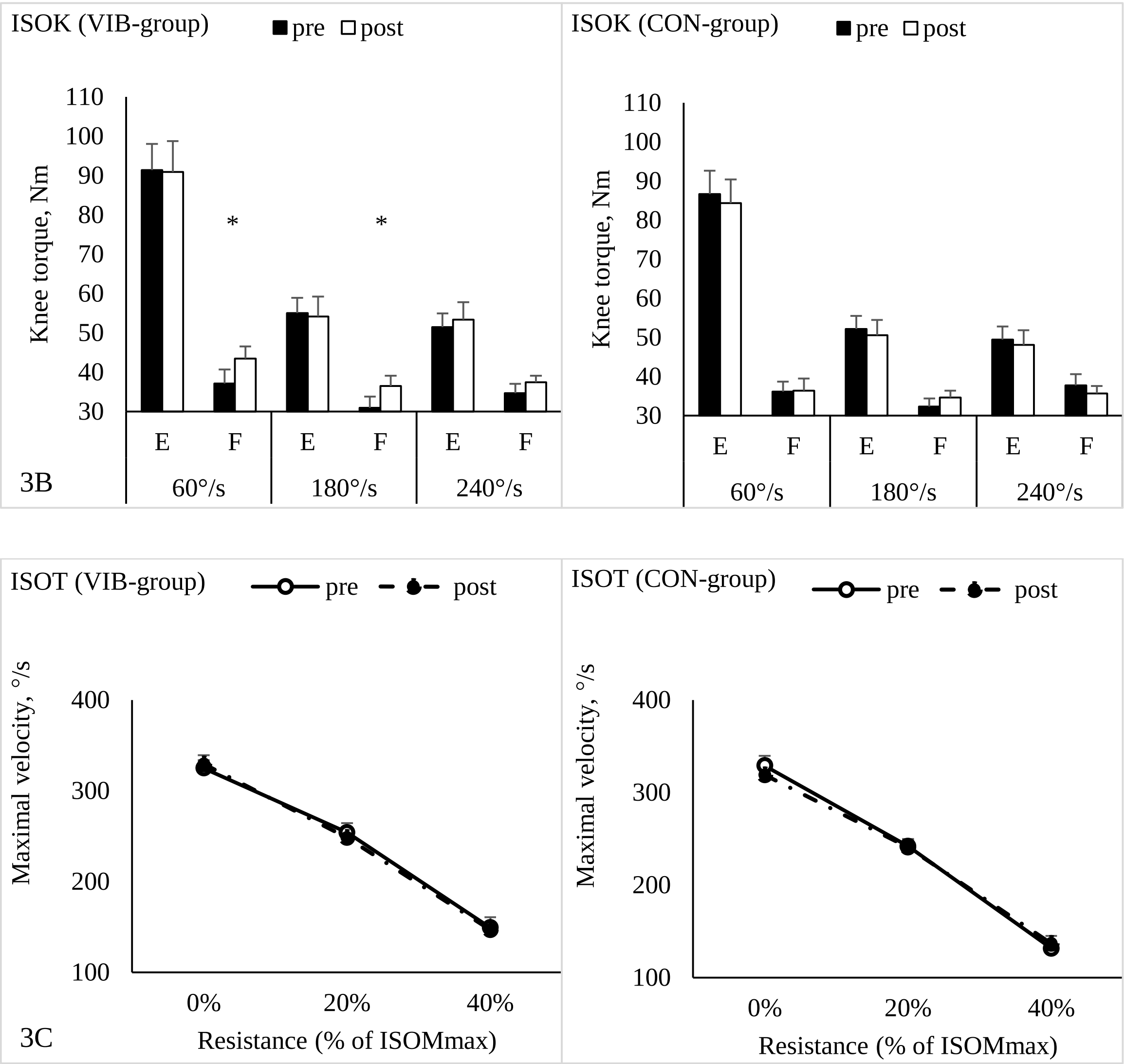


Figure 3. Mean and SE before (pre) and after (post) 6 months of local vibration training.
NOTE. VIB – vibration group, CON – Control group, ISOM (3A) – isometric muscle strength, ISOK (3B) – isokinetic muscle strength, ISOT (3C) – isotonic muscle strength.
* Within-group difference: a significant difference between baseline and post measures (P<0.05)

Bone mineral density

As shown in Table 3, total hip BMD did not significantly change over time in both vibration and control groups, and additionally, no between-group difference was observed between the two groups (P>0.05).

Table 3. Mean Changes and Between – Group Differences in Muscle Strength, Shuttle Walk Test (SWT) and Modified Physical Performance Test (mPPT)

Parameter	Vibration	Control	Between-group difference	
			Mean	P-value
Total hip BMD	–1.34 (±2.56)	–0.23 (±2.18)	–1.11	0.16
Muscle mass	–0.759 (±3.48)	–1.161 (±4.38)	+0.410	0.87
Fat mass	+0.916 (±4.49)	–1.896 (±8.07)	+2.812	0.17
Physical performance				
• mPPT, points	+0.21 (±2.12)	+0.47 (±2.87)	–0.26	0.65
• SWT, m	–1.21 (±39.4)	+4.73 (±55.0)	–5.94	1.00

NOTE. Values are presented as a percentage of the baseline measures if not indicated differently.

Muscle mass

Total muscle or fat mass volume did not change significantly over time in either the vibration or the control group and no between-group differences were observed between the two groups (P>0.05, Table 3).

Physical performance

As shown in Table 3, no within-group difference in physical performance – mPPT or SWT over time was observed in either the vibration or the control group (P>0.05). Similarly, no between-group differences were found between the intervention and the control group after the 6-month training period (P>0.05).

DISCUSSION

This was the first study to investigate the feasibility, safety and compliance of a 6-month local vibration applied 5 times a week (30 – 45 Hz, 1.71 – 3.58 *g*) in postmenopausal women. We hypothesized that the specific local vibration program would be a feasible and safe training method to improve musculoskeletal performance in postmenopausal women.

Overall, no adverse effects due to local vibration were reported and the training intensity was well tolerated. Although, the participants reported that 5 days/week training was time consuming, the average compliance with the intervention was excellent (X: 96.5%). Moreover, the participants did not consider the training as difficult, suggesting that local vibration training may be a feasible training program for postmenopausal women.

The main outcomes of the study indicated that the specific vibration program has potential beneficial effects on some aspects of knee muscle strength, but failed to affect bone formation, muscle mass or physical performance in postmenopausal women.

In this study, a local vibration training applied on the hip and mid-thigh resulted in an improvement in some aspects of knee isometric and isokinetic muscle strength. Isometric knee extension strength of 60° and 90° increased significantly by 12.88% and 6.61%, respectively, in the vibration group after the 6-month local vibration training. The standardized Cohen's *d* effect size reflected a small to large mean effect on muscle strength as a result of the vibration intervention, which supports the likelihood of a clinically meaningful effect only on muscle knee strength in a larger randomized controlled trial.

Only very few studies investigated the effect of locally applied vibrations on muscle strength.[27,28] In a study by Pietrangelo et al.[28] local vibration training was applied close to the tendon of the quadriceps once to three times a week to a group of male and female elderly (65 – 85 years of age). Twelve weeks of high-frequency local vibration training (frequency of 300 Hz) resulted in a significant improvement between 41.7% and 81.2% in isometric knee extension strength. Vibration frequency used by Pietrangelo et al. was much higher compared to our study (300 Hz to 30 – 45 Hz), however, they did not reported the applied amplitude and acceleration of the vibration and the sample size was very small which might have contributed to the different findings. In a study by Lapole and Pérot,[27] 14 days of locally applied vibration (50 Hz, 0.2 mm) directly to the Achiles tendon resulted in a greater triceps surae force production. The authors concluded that the specific local vibration training may be beneficial to persons who are not suitable for WBV training.

In addition, our findings are in line with previously reported WBV studies in elderly.[21,22,29] In the study by Verschueren et al.[21] 6-month WBV (35 – 40 Hz, 2.28 – 5.09 *g*) resulted in 15% and 16% a net benefit of isometric and dynamic knee strength in postmenopausal women, respectively. Likewise, in another study with WBV, 12 months of vibration training improved isometric knee strength by 9.4% among older adults.[29] Roelants et al.[22] reported a significant increase in isometric (15%) and dynamic (16.1%) knee extensor strength after 6 months of WBV (35 – 40 Hz, 2.28 – 5.09 *g*) in elderly. It has been suggested that vibration training may increase muscle strength by similar mechanisms as during resistance training.[30] The first mechanism of adaptation is neural adaptation including an increase in motor unit synchronization, inhibition of the antagonist muscles, or co-contraction of the synergist muscles.[31] Strength gain may also increase the ability of motor units to fire briefly at very high rates.[32] After several months of training, the changes in the morphological structure of the muscle become dominant.[33] However, the present study failed to find any changes in muscle mass after 6 months of local vibration training and therefore, the neural adaptations seem a more relevant mechanism of strength gain. The supine lying static position taken by the participants may contribute to the lack of changes in other aspects of isometric and dynamic muscle strength. In addition, the older age is associated with a decline in the number of muscle spindles which leads to a reduced muscle sensitivity to mechanical loading.[34]

In addition, present findings showed a significant improvement in isokinetic knee flexion strength of 60°/s and 180°/s in the vibration group by 23.00% and 24.06%, respectively. This improvement in the flexion knee strength is surprising as the vibration was applied directly to the quadriceps and the participants were in a static supine-lying position.

The current study failed to show any effect of local vibration training on knee isotonic muscle strength (resistance of 20% and 40% of the isometric maximum). In contrast, one WBV study did report an improvement in knee-extension speed of movement with an external resistance of 1%, 20%, 40%, and 60% of isometric maximum after 6 months of vibration in postmenopausal women.[22] It has been suggested that the vibration training results in a more rapid activation and training of high-threshold motor units,[35] which contributes to maximal velocity muscle strength. However, the present findings cannot confirm these suggestions. In addition, the isometric maximum – 90° improved significantly in the vibration group after the local vibration training, which resulted in higher tested resistances (20% and 40%) compared to baseline.

The results of the present study failed to show an effect on BMD after 6-months of local vibration training. In contrast to our findings on BMD, a few randomized control trials have shown a significant increase in the BMD of the total hip, femoral neck and/or lumbar spine after WBV training.[21,23,36,37] Following 6-month WBV training (35 – 40 Hz, 2.28 – 5.09 *g*), Verschueren et al.[21] reported a net benefit of 1.5% BMD at the hip in postmenopausal women. Gusi et al. found a net benefit of 4.3% BMD at the femoral neck in postmenopausal women who followed 8 months of vibration intervention (12.6 Hz, 3.3 *g* – lateral, 0.7 *g* – vertical) in comparison with walking group.[36] WBV training with vitamin D supplementation (35 – 40 Hz, 1.6 – 2.2 *g*) improved BMD of the hip compared with baseline in postmenopausal women.[38] However, vibration intervention did not result in an additional increase in BMD of the hip compared with controls independently of the additional vitamin D supplementation.

Up to our knowledge, this study was the first to assess the effects of locally applied vibration training on BMD. In the present study, the lack of changes in bone density may be a result of different factors. The vibration loading was considered as reasonable for postmenopausal women and was based on loadings as induced by whole-body vibration training shown before to be effective on bone formation.[21] However, the applied frequencies between 30 and 45 Hz and accelerations between 1.71 and 3.58 *g* might not have been optimal to induce higher bone responses. Moreover, while standing on a WBV platform and performing dynamic exercises, the subject experiences both ground reaction and muscle forces which contribute to bone formation.[39] However, local vibration training was in a supine lying static position and therefore, the participants were not exposed to weight-bearing loads, which may explain the lack of changes in bone density. Additionally, fat mass around the hip may alter the transmission of the vibration signal from the vibrators to the bone. The positioning of the vibrators on the hip may not have been optimal enough to reach the target zones sufficiently.

Study limitations

Our study has limitations and the results should be interpreted in the context of its design. First, our sample size was small, and we acknowledge that this was an exploratory pilot study with no formal sample size calculation. Moreover, due to the intensive vibration training, it was difficult to recruit more participants who could meet the inclusion and exclusion criteria, and who showed a willingness to participate in the trial. Second, we tested only one training regime – training 5 days/weekly, frequency between 30 and 45 Hz, and acceleration between 1.71 and 3.58 *g*. The vibrators were positioned only on the mid-thigh and around the hip which might not have been an optimal training program. Furthermore, the participants took only a supine lying static position and they did not perform simultaneously any dynamic exercises. Third, when the findings of the present study are interpreted, it should be mentioned that significant differences in weight and body mass index were found at baseline between the vibration and the control groups. However, all other baseline tests did not differ between the groups which makes them comparable by means of physical performance, bone mineral density and muscle strength. The manner by which the higher weight influenced the transmission of the vibration signal from the vibrators to the hip cannot be further discussed. Finally, our preliminary findings may only be generalized to a select group of older people and not to younger adults or older men.

CONCLUSIONS

In a conclusion, the present training protocol of 6 months locally applied vibration on the hip and mid-thigh was feasible for the elderly with no side effects, did improve some aspects of muscle strength but had no effect on bone mineral density, muscle mass, and physical performance in postmenopausal women.

Suppliers' list:

a. Powerbox AB, Västra Storgatan 22, Gnesta, Sweden
b. Micro-electro-mechanical system, SMB380, Bosch Sensortec Gmbh, Reutlingen, Germany
c. Hologic, Waltham, MA, USA
d. Biodex Medical Systems Inc, 20 Ramsay Road, Shirley, New York, 11967-4704.
e. Siemens Sensation 16; Forcheim, Germany
f. STATISTICA Inc, Version 9, 2300 East 14th Street Tulsa, OK 74104, USA

Acknowledgments

Supported by the Research Foundation Flanders (FWO), Brussels, Belgium (project nos. FWO-G0488-08, FWO-KN-1.5.017.08). No commercial party having a direct financial interest in the results of the research supporting this article has conferred or will confer a benefit on the authors or on any organization with which the authors are associated.

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GENERAL DISCUSSION

The scope of this doctoral project was to study a variety of vibration application protocols in an attempt to broaden different vibration training methods to different populations. In **Chapter 1** of the doctoral project we aimed to investigate the extent to which variations in the vibration excitation patterns (frequency, amplitude) alter the transmission of the stimulus from a vibration platform to the upper body and potentially contribute to beneficial or detrimental effects to muscle and bone. In **Chapter 2**, we tested a new vibration device with a cable-pulley resistance system attached to a vibration platform. The aim of the study was to channel the vibration indirectly from the platform to the upper body and potentially broaden the impact of vibration training to the upper-limb muscle groups. In **Chapter 3,** a 6-week randomized controlled pilot study for patients with chronic stroke was conducted in an attempt to broaden the WBV training to a different populations than young adults and healthy elderly. In **Chapter 4**, a different form of vibration training – local vibration training, was applied in an attempt to broaden the impact of vibration intervention to frail elderly. The study was designed as a randomized controlled pilot trial for postmenopausal women who underwent 6 months of locally applied vibrations at the mid-thigh and around the hip.

The general discussion will focus on the summary and interpretation of the main outcomes from the described chapters. We will also provide some recommendations for future research.

Summary of the main findings

As described in **Chapter 1**, vibration transmission was assessed over a wide range of accelerations (from 0.33 to 7.98 *g*) and frequencies (30 to 50 Hz) in eight clinically healthy volunteers performing 3 different static body postures – high squat (135°), deep squat (110°) and erect stance. The main findings showed a significant attenuation of the platform accelerations transmitted from the feet to the head. Knee bent posture significantly diminished vibration transmission at the hip, spine and the head compared to erect stance and vibration transmission to the spine was significantly lower in deep versus high squat. Vibration increased the muscle activity in most leg and hip muscles during both squat postures, although, on average, no clear dose-response relationship between the acceleration and/or frequency and muscle response was found. Based on the findings of this study we concluded that the specific vibration parameters used in the present study could be considered as safe and suitable for a vibration training program.

As reported in **Chapter 2**, fifteen clinically healthy participants performed 3 different arm exercises – biceps curl, triceps curl, and lateral raise. Vibration transmission to the upper body was assessed over a wide range of accelerations (from 1.90 to 5.98 *g*) and frequencies (from 25 to 40 Hz). The main findings showed a significant attenuation of the platform accelerations transmitted through the vectran cables to the upper body. The applied vibration increased the muscle activity of biceps brachii, triceps brachii, deltoid and upper trapezius muscles significantly only during biceps curl exercises. We concluded that the cable-pulley resistance system on a vibration platform channels the vibration safely from the platform to the arms and induces additional muscle activation in some arm muscles only when biceps curl exercises were performed.

As described in **Chapter 3**, we conducted a randomized controlled pilot study of a 6-week intensive whole body vibration training program (3x/week, 1.7 and 2.5 mm; 35 and 40 Hz) in adults with chronic stroke. Fifteen patients with chronic stroke were randomly assigned to an intervention (n=7) or a control group (n=8). The main findings of this study showed that the intensive WBV program was well-tolerated by the patients and no adverse effects due to the vibration were reported. The whole body vibration intervention resulted in significant between-group differences in favor of the vibration group only in isometric knee extension strength of 60° after 6 weeks of intervention and in isokinetic knee extension strength (velocity of 240°/s) after a 6 weeks follow-up period, both for the paretic leg. Postural control improved in the intervention group after the WBV training when the patients had normal vision and a sway referenced support surface. Muscle spasticity was not affected by vibration. We concluded that the specific intensive WBV might potentially be a safe and feasible way to increase some aspect of lower limb muscle strength and postural control in adults with chronic stroke.

As reported in **Chapter 4**, we conducted a randomized controlled pilot trial of 6 months of local vibration training program (30 – 45 Hz; 1.71 – 3.58 *g*) in postmenopausal women. Thirty-five elderly were randomly assigned to an intervention (n=17) or a control group (n=18). The main findings of this study showed that 6-month local vibration training resulted in significant between-group difference in favor of the vibration group only in isometric knee extension strength of 60°. Bone mineral density, muscle mass and physical performance did not change over time in either of the groups. We concluded that the specific local vibration training protocol might be considered as suitable training program to increase some aspects of knee muscle strength, but had no effect on bone density, muscle mass and physical performance in postmenopausal women.

Interpretation of the findings

In general, the approach used in this doctoral thesis aimed to expand the impact of vibration training to different body parts of interest and in different populations. The most common vibration training method is whole-body vibration training. WBV training has widely been promoted among trainers and patients as a beneficial form of training to improve musculoskeletal performance.[1-3] Therefore, it remains important to evaluate the most optimal vibration protocol from an efficacy and a safety perspective.

1. Vibration training and its efficacy perspective

This doctoral thesis was the first to evaluate the transmission of a wide range of vibration accelerations and frequencies through the entire body and the associated muscle response, body posture and inverse kinematics. The increase in EMG during vibration exposure indicated that WBV did influence lower- and upper-limb muscle activation (Chapter 1 and Chapter 2, respectively) which has previously been demonstrated in other vibration studies.[4-11] We can speculate that these specific methods of vibration training may be used among healthy adults in a longer-term as a training method to improve muscle strength and power. It is important to emphasize that this doctoral thesis failed to show a clear dose-response relationship between vibration excitation patterns and the size of muscle response of both upper- and lower-limb muscles. There were no significant main frequency and/or acceleration effects which may be explained by the wide variety in muscle activity between the participants and the relatively small sample size in both studies. Therefore, it is difficult to conclude which vibration training parameters would elicit larger muscle responses for the studied muscle groups.

We tested a new vibration platform with a cable-pulley resistance system with two different loads (2.5 kg and 5 kg) which did not provoke a different muscle response. The possible reason may be that the loads were too light to induce additional muscle activation. Additional muscle activation could be induced if lateral raise exercises were performed in another more efficient manner. The length of the cables (2.2 meters) gives the possibility to perform different combinations of exercises. The increased range of motion during lateral raise exercises could lead to longer muscle activation resulting in higher muscle response which needs to be studied further. In addition, if the participant was facing away from the platform, the range of motion of Biceps brachii and Triceps brachii would have matched. The activation of Triceps Brachii may be stronger if the participants perform the triceps curl exercise facing away from the platform.

When discussing the improvement in isometric knee muscle strength following vibration treatment (Chapters 3 and 4), it might be speculated that neural rather than muscular adaptation lead to the muscle strength increases. Neural adaptation includes an increase in motor unit synchronization, an inhibition of the antagonist muscles, the ability of motor units to fire briefly at very high rates, or co-contraction of the synergist muscles.[12,13] After several months of training, the changes in the muscular structure become dominant.[14] In our studies the changes in the morphological structure of the muscle are very unlikely. Vibration training period adapted for the patients with chronic stroke was very intensive but rather too short to induce changes in muscle structure. The present doctoral thesis failed to find any changes in muscle mass due to locally applied vibration training, and therefore, the neural adaptations also seem a more relevant mechanism of strength gain.

It is well-known that stretched muscles are more sensitive to vibration stimulation[15] and therefore, respond to vibration with a stronger contraction.[8] Postmenopausal women who underwent 6 months of locally applied vibration therapy were asked to remain relaxed during the training sessions (Chapter 4). The participants found it difficult to contract their muscles voluntarily during the vibration bouts which lasted between 30 and 60 seconds. Additional exercises could have resulted in a larger increase in muscle strength due to vibration.

The patients with chronic stroke (Chapter 3) performed additional exercises on the platform which included: standing on toes, high and deep squat, wide stance squat, and one-legged squat. However, this raises the question if_the absence of a third group receiving no therapy but performing the same exercises makes it difficult to determine whether the improvements in muscle strength and postural control was due to the vibration. In a study by Delecluse et al.[16] healthy adults were randomized in four groups – a whole body vibration group, a resistance-training group, controls and a placebo group in terms to determine if the effect in the vibration group was a result from the performed exercises or the vibration intervention. The participants in the placebo group performed the same exercises on the platform, but the acceleration of the vibration stimulus was only 0.4 *g* with a negligible amplitude. Isometric and isokinetic muscle strength improved only in the vibration and resistance-training group, however, no significant increase was found in controls and in the placebo group. The outcomes in the study of Delecluse et al. clearly indicated that the improvements in muscle strength in the vibration group were a result of vibration training and were not related to a placebo effect of the performed squat exercises. We may speculate that in the current doctoral project, the improvement in isometric muscle strength was a result of vibration training. However, we cannot exclude that in the present population tested this improvement of knee muscle strength and postural control can be a result of the different dynamic exercises performed on the platform. It would have been interesting to include patients in a resistance training group to perform the same exercises on the platform but without vibration (placebo group) in order to study the ‘real’ effect of vibration training on neuromuscular performance.

As mentioned above, the locally applied vibration loading (Chapter 4) was based on loadings induced by whole-body vibration platform (35 – 40 Hz, 2.28 – 5.09 *g*).[1] The same commercially available platform and its vibration excitation parameters were tested in Chapter 1 in order to optimize the vibration training stimulus from an efficacy perspective and to investigate the most optimal and beneficial loading on muscles and bones. The transmission of the vibration signal diminished when propagating from the platform through the body. The average transmission of the stimulus was reduced at the hip and ranged between 0.04 to 0.17 times RMS of the platform. Applying vibration training locally and in a direction different than the one coming from a whole-body vibration platform may be more efficient. It well-known that the bone responses to high mechanical magnitude stresses and adapts in accordance with the trajectory of the externally applied forces. It is considered that “abnormal” mechanical loading at different points within the bone tissue may have a more dramatic effect on bone responses than “normal” loadings (so-called neutral axis).[17]

However, this doctoral project failed to find any changes in bone mineral density after 6 months of locally applied vibration training in postmenopausal women. Several reasons might be put forward to explain the lack of changes in bone density. First, the applied frequencies (between 30 and 45 Hz) and accelerations (between 1.71 and 3.58 *g*) of the local vibration loading might not have been optimal to induce higher bone responses. Second, bone responses are a result of the interaction between muscle contraction and gravitational loading. These forces may act in a different way when whole-body or local vibrations are applied.[18] While standing on a WBV platform, the subject experiences weight-bearing loads which might contribute to bone formation.[19] However, during local vibration, the participants were not exposed to weight-bearing loads, which may explain the lack of changes in bone density.

Additionally, fat mass around the hip may alter the transmission of the vibration signal from the vibrators to the bone. Another reason may be that our group of postmenopausal women was too heterogeneous to show an improvement in BMD after 6-months of vibration training. It might be possible that the vibration training has an effect on bone mostly in groups with compromised BMD.[20,21] Moreover, it is suggested that some individuals might be more sensitive to vibration exposure and may have a better bone response and thus, may benefit more from the vibration training compared to other individuals who might not be genetically responsive to vibration intervention.[22] However, the current findings did not indicate that some persons are genetically more responsive to locally applied vibration therapy than others.

2. Vibration training and its safety perspective

In addition to the desired benefits associated with vibration training, the potential deleterious effects as a result of vibration intervention should be considered. The dangers associated with long-term effects of occupational chronic vibration exposure on human body are well-known.[23] However, it seems more difficult to evaluate the safety standards for the different types of vibration training due to many more factors that need to be considered. Different combinations of frequency, amplitude and duration of vibration exposure are likely to affect the human body differently.

We followed basic evaluation method from ISO2631 (1997)[24] in order to evaluate the safety aspect of whole body vibration training. Based on the estimation of Exposure Limit Values (ELV), it was concluded that the vibration parameters (30 – 50 Hz, 2.25 – 7.98 *g*) delivered by the commercially available vibration platform can be considered as reasonably safe on a daily basis for 15 minutes, especially when avoiding high amplitude and high frequency settings (Chapter 1). Similar commercially available platform and vibration parameters (35 – 40 Hz, 1.7 – 2.5 mm/2.28 – 5.09 g) were used to train the patients with chronic stroke (Chapter 3). These participants who underwent 6 weeks of intensive WBV training, tolerated the vibration program well and reported no adverse effects due to vibration. Therefore, the specific intensive vibration training for chronic stroke patients may be considered as safe and suitable training method. However, one could argue that the participants in Chapter 1 were only healthy adults and therefore the findings should be discussed with caution when addressed to patients with neurological disorders. Patients with chronic stroke have muscle weakness which results in lower muscle forces.[25,26] It may be speculated that the lower muscle forces could alter the damping properties of the muscles and thus, alter the transmission of the vibration signal through the body up to the head.[27]

Local vibration loading and its parameters (30 – 45 Hz, 1.71 – 3.58 *g*) were based on loading as induced by standing on a commercially available vibration platform (35 – 40 Hz, 2.28 – 5.09 *g*) that was shown to have a positive effect on musculoskeletal performance (Chapter 4, Appendix 1).[1] The participants tolerated the training protocol well and no adverse reactions were reported due to vibration. These vibration parameters were shown to be safe in healthy volunteers who trained on a whole-body vibration platform (based on ISO norms). It should be taken into account that lower-limb muscles alter the transmission of the signal from the platform to the upper body, which is not the case when applying vibration locally. As a result, vibration transmission at the lumbar spine (L3) of the locally applied signal was measured with accelerometers. RMS acceleration at L3 ranged from 0.04 to 0.2 g (data not previously shown). Therefore, we consider that the specific local vibration training may be considered as safe.

Regarding the specific vibration training for upper-limb muscles, we followed a basic evaluation method from ISO5394-1:2001[28] to evaluate the safety aspect of vibration training. Participants could train up to 172 minutes before the daily Exposure Limit Value (ELV, 1.15 m/s^2) was reach. It seems suitable and safe to apply vibration indirectly via cable pulley system, because the vibrating barbells or dumbbells which are applied directly to the hand in other vibration studies may result in harmful effects on humans.[4,23,29] Even more, cable system allows the subject to perform a wider range of strengthening exercises.

In conclusion, this doctoral project studied the feasibility, safety and compliance of new vibration training protocols in an attempt to broaden the impact of vibration training to different populations. Based on ISO norms (ELV) and participants' subjective feelings, we may conclude that these specific vibration protocols may be safe and feasible training programs to improve neuromuscular in different populations including patients with chronic stroke and postmenopausal women.

Critical considerations

This doctoral project has several critical considerations which need to be addressed.

An adequate **sample size** is necessary to obtain strong study power. First, we acknowledge that both randomized controlled trials (Chapter 3 and 4) were designed as exploratory pilot studies and thus, the formal sample size was not calculated. The reason was that the vibration protocol which we used in Chapter 3 (n = 15) was more intensive in comparison with the vibration training programs for patients with chronic stroke compared to the studies for adults with chronic stroke which have been reported so far. In Chapter 4 (n = 35) we applied a different form of vibration training – local vibration training in an attempt to broaden the impact of vibration intervention to frail postmenopausal elderly. Therefore, these studies were conducted as pilot studies in an attempt to assess the feasibility, compliance, and possible negative effects. Hence, based on our findings, larger randomized controlled trials may be designed to further investigate the possible positive effects of these two novel vibration training protocols.

Another consideration is related to the studied **populations** in the different studies. First, in Chapter 1 and 2 we only addressed healthy, young volunteers and our data is not representative for other populations. However, it seemed crucial to assess the transmission of the vibration signal up to the head firstly in healthy participants and then to apply this specific training to other populations including frail elderly or patients with neurological disorders. Second, in Chapter 1 and 2, we did not evaluate the training background of the participants before the measurements, which might influence the muscle response due to vibration training. In Chapter 3, most of the stroke patients had only mild to moderate physical impairments and were ambulatory-independent and thus, our findings cannot be referred to patients with more severe impairments or patients with acute stroke. It should be underscored that patients with more severe impairments might not be able to train on the vibration platform. Therefore, applying the vibration training locally might be more beneficial for this patient’s group. Finally, due to the strict inclusion and exclusion criteria for enrolment in the local vibration training, the participants in Chapter 4 may not be representative for the overall elderly population. However, we took into consideration that the applied vibration training program was intensive and the participants trained 5 times a week. Therefore, we recruited mainly postmenopausal women (above 65) in relatively good health who were able to apply the vibrators without additional help.

Concerning the **methodological and practical considerations**, it should be underlined that we placed custom-made skin-mounted accelerometers to measure the transmission of the vibration signal through the entire body (Chapter 1 and 2). This type of accelerometers allowed movements of soft tissue and skin, which potentially interfere with the transmitted acceleration detected by the accelerometers. More accurate bone-mounted accelerometers were used in the study by Rubin et al.[30] and the pins were directly fixated on the spine and the hip. This methodology could be more precise but also more invasive and harmful.

In Chapter 1 and 2, the variation in muscle responses between the participants was very high which may have influenced the present findings. However, in both Chapters, only a single data-collection session was performed, without re-test, which did not allow to assess the differences in response to vibration within subjects.

We evaluated the postural control in the patients with chronic stroke with The Sensory Organization Test (Chapter 3). So far, the changes in postural control in stroke patients following vibration training were measured via different balance tests including Berg Balance Scale,[31-33] center-of-pressure,[34,35] Tinetti Gait Test,[32] Barthel Index,[32] and etc. It still remains unclear which test is the most relevant one in order to assess the postural control in the clinical practice.

In Chapter 4, we tested only one vibration training program – frequency between 30 and 45 Hz, and acceleration between 1.71 and 3.58 *g*. Vibration training was applied 5 days weekly which might be too much for some of the participants. Additionally, the vibrators were positioned only in supine lying static position on the mid-thigh and around the hip which might not have been the most optimal training program. In addition, the participants did not perform any dynamic exercises. The type of exercises performed in our studies are limited. This consideration will be discussed further as a recommendation for future research.

Recommendations for future research

Future studies are still recommended to identify more precisely the different vibration application forms (whole body and local vibration) for different populations.

One future research direction might be related to the number of repetitions and type of exercises performed during vibration training. A typical fitness training includes multiple-repetition sets of different loaded dynamic exercises. Multiple-set training leads ultimately to a significant decrease in the speed of repetitions and muscular fatigue which may alter the transmission of the vibration signal through the body.[36,37] In addition, it has been shown that loaded dynamic exercises with vibration are more beneficial over a loaded training without vibration.[5,38] Martin and Park[39] reported that different loads during vibration training result in different levels of muscle tensions which may alter the muscle response due to increased motor unit synchronization. An additional loading facilitates the transmission of the vibration signal to more muscle groups as a result of the increased muscle stiffness. Therefore, future research may investigate the dose-response relationship between different vibration excitation patterns and muscular activity while multiple-repetitions of loaded exercises are performed. In addition, so far, only the study by Marin et al.[40] reported that WBV (30 and 46 Hz, 2.5 and 1.1 mm) can increase the muscle activation (EMG) of both upper- and lower-muscle groups in a group of healthy elderly. However, the safety aspects of vibration exposure were not evaluated. Thus, it remains important to evaluate the safety aspects of vibration training among different populations including frail elderly or patients with neurological disorders.

Future studies need to be conducted to investigate not only the effects of vibration training on muscle strength and postural control in patients with chronic stroke but also the effect of WBV on bone mineral density and bone turnover markers. Patients with chronic stroke have higher risk of fractures compared to age-matched controls.[41] The risk of fracture is more common in the paretic leg and is associated with higher rate of falls (due to muscle weakness and balance instability) and decreased strength of the bones in these patients.[42] It is well-known that patients with chronic stroke experience a loss in bone strength and bone mass on the paretic leg in comparison with the non-paretic leg.[43] The importance of bone maintenance among patients with chronic stroke is crucial. It has been shown that high-magnitude exercises could be beneficial to maintain bone loss in post-stroke conditions.[44] Vibration training as an alternative training method to high-intensive and resistance training exercises, has been shown to increase bone mineral density in different populations.[1,45,46] Hence, it would be interesting to investigate the effect of vibration training on bone mineral density in patients with chronic stroke. In our randomized controlled trial, we studied only the effect of vibration intervention on muscle strength and postural control. Due to the relative short training period, the effect of the specific intensive WBV program on bone could not be assessed. Therefore, future studies with a longer period of training are necessary to provide a better overview of the effects of vibration on musculoskeletal performance in adults with chronic stroke. Further studies could test not only the muscle strength and balance control, but also the incidence of falls of patients with stroke.

This doctoral project was the first to investigate the effects of a new form of vibration training – local vibration training on musculoskeletal performance in postmenopausal women. The vibrators used in study 4 (Chapter 4) were custom-designed vibrators and, the frequency and acceleration produced by the vibration machines were limited. Vibration frequency delivered by the vibrators ranged between 30 and 45 Hz and vibration accelerations ranged between 1.71 and 3.58 *g* as measured by accelerometer. Therefore, it would be interesting to investigate a larger range of vibration excitation patterns and a dose-response relationship between the applied vibration parameters and the induced muscular activity. A different daily treatment dose and a different treatment period may induce a more optimal response on muscle strength and bone density. Furthermore, a more optimal musculoskeletal response might be achieved if the vibration stimulus is applied in other loading directions. Further studies should quantify the effect of positioning of the local vibration device on musculoskeletal performance.

Moreover, the participants in the vibration group did not perform any dynamic exercises while lying in supine position (Chapter 4). It has been shown that vibration training was more efficient when dynamic exercises were performed on a vibration platform.[47] In order to obtain a greater improvement in muscle strength, future studies might focus on performance of various dynamic exercises while local vibration is applied. In addition, a larger randomized controlled trial should include more participants divided into subgroups according to the severity of their osteoporosis and physical performance. Furthermore, it may be interesting to investigate the effect of local vibration training on BMD in other populations including elderly men or adults with compromised bone mineral density.

Finally, although, we showed that 6 months of local vibration training is a feasible training method to improve knee muscle strength in postmenopausal women (Chapter 4), it remains unclear if this improvement in muscle strength would persist over time. Long-lasting effects of vibration training on neuromuscular performance are still disputable. Most of the studies reported only immediate effects after vibration training rather than the residual effects over time. It has been shown that 1 year of WBV in elderly men resulted in an improvement of isometric and concentric muscle strength.[48] Recently, a 1-year follow-up period in the same population of elderly men showed that knee muscle strength did no longer differ from the baseline measures.[49] Therefore, it might be interesting to conduct a larger randomized controlled trial which would include a follow-up period in order to determine the long-term effects of the locally applied vibration training.

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SUMMARY

Vibration training has widely been promoted as a beneficial form of training exercise to improve muscle performance, bone density and postural control in athletes, adults and elderly. Vibration training can be applied either to the whole body or locally in an attempt to broaden the impact of vibration to different populations.

The most common and well-studied vibration approach is the whole-body vibration training (WBV). WBV training has been reported to have a positive effect on musculoskeletal performance in athletes, sedentary adults and postmenopausal women. However, several studies found no changes in musculoskeletal performance after short- or long-term WBV intervention and therefore, the results of the different WBV studies remain inconclusive and often inconsistent. The reason for this inconsistency may be related to the different vibration excitation patterns (frequency, amplitude and duration) applied in the various studies. Only a few studies have investigated the dose-response relationship between the applied vibration parameters and the size of the muscle response, and thus, the extent to which different vibration parameters potentially contribute to positive or negative effects to human body. Further studies are necessary to evaluate the vibration training stimulus from an efficacy and a safety perspective.

While the effects of whole-body vibration on musculoskeletal performance are well-documented in athletes, healthy adults and elderly, further research is still necessary to evaluate the possible beneficial effects of whole-body and local vibration training on muscle strength or bone density in other populations including neurological patients or frail elderly. Therefore, this doctoral project studied different forms of vibration application forms – whole-body and local vibration, in an attempt to broaden the impact of vibration training to different populations.

In the first part of this doctoral project we evaluated the dose-response relationship between a wide range of vibration frequencies and accelerations, and the induced muscular activity. Additionally, the transmission of vibration signal through the human body was assessed and the safety aspect of different types of whole-body vibration training were measured. In **Chapter 1**, we tested the transmission of vibration from a whole-body vibration platform through the body up to the head and the muscular activity of lower limb muscles was measured. **In Chapter 2**, a new vibration device with a cable-pulley resistance system attached to a vibration platform was tested in an attempt to channel the vibration indirectly

from the platform to the upper body and potentially broaden the impact of vibration training to the upper-limb muscle groups.

The main findings in both studies showed a significant attenuation of the platform accelerations transmitted through the body up to the head. Vibration increased the muscle activity in most of the studied muscles during vibration exposure, however, on average, no clear dose-response relationship between the acceleration and/or frequency and muscle response was found. Based on the findings of these studies we concluded that the specific vibration parameters used in this doctoral thesis could be considered as safe and suitable for a vibration training program.

In **Chapter 3**, we conducted a 6-week randomized controlled pilot study for patients with chronic stroke in an attempt to broaden the WBV training to different populations than young adults and healthy elderly. This was the first study to show that the specific intensive WBV intervention may be a safe and feasible way to increase some aspect of lower limb muscle strength and postural control in adults with chronic stroke.

In last **Chapter 4**, we applied a different form of vibration training – local vibration training, in order to broaden the influence of vibration training to frail elderly. Therefore, a group of postmenopausal women trained 6 months of locally applied vibrations at the mid-thigh and around the hip. This was the first randomized controlled pilot study to show that the specific local vibration training program might be considered as suitable training program to increase some aspect of knee muscle strength in postmenopausal women. However, bone density, muscle mass and physical performance did not change due to the vibration training.

In conclusion, this doctoral project was the first to study different methods of vibration training – whole-body and local, in order to broaden the impact of vibration training to different populations. The present findings contribute to understand better the possibility to train not only healthy adults, but also patients with chronic stroke and postmenopausal women. We found that vibration training may be a feasible and safe training method to increase muscular performance in different populations.

However, it still remains unclear what the most optimal vibration training program is in terms of vibration parameters (frequency and amplitude), duration of vibration exposure and rest periods, number of bout per session, number of sessions per day, type of exercises, and etc.

SAMENVATTING

Vibratietraining wordt op grote schaal gepromoot als een effectieve vorm van training om spierprestatie, botdensiteit en posturale controle te verbeteren bij atleten, volwassenen en ouderen. Vibratietraining kan zowel op het hele lichaam als lokaal toegepast worden met als doel de effecten van trillingen op verschillende bevolkingsgroepen te vergroten.

De meest voorkomende en goed bestudeerde vorm van vibratietraining is de whole-body vibratietraining (WBV). Het is gekend dat WBV-training een positief effect heeft op spierprestaties bij atleten, sedentaire volwassenen en postmenopauzale vrouwen. Echter, verschillende andere studies vonden geen veranderingen in spier prestaties na een korte- of langdurige-WBV, waardoor de resultaten WBV nog steeds onduidelijk en inconsistent blijven. De reden voor deze inconsistentie kan mogelijks gerelateerd worden aan de verschillende excitatiepatronen van de vibratie (frequentie, amplitude en duur) in de verschillende onderzoeken. Slechts enkele studies onderzochten de ‘dosis-respons relatie’ tussen de toegediende vibratieparameters en de omvang van de spierrespons, en dus de mate waarin verschillende vibratieparameters kunnen bijdragen tot positieve of negatieve effecten op het menselijk lichaam. Verdere studies zijn nodig om de vibratietrainingsprikkel te evalueren met het zicht op efficiëntie en veiligheid .

Hoewel het effect van WBV reeds goed onderzocht werd in atleten, gezonde volwassenen en ouderen, is verder onderzoek nog nodig om de mogelijke gunstige effecten van globale en lokale vibratietraining op spierkracht of botdensiteit te evalueren in andere populaties waaronder neurologische patiënten of kwetsbare ouderen. Daarom onderzocht dit doctoraatsprojectverschillende toedieningsvormen van vibratie - globale en lokale trillingen, in een poging om de impact van vibratietraining op verschillende populaties te verbreden.

In het eerste deel van dit doctoraatsproject werd de ‘dosis-respons relatie’ geëvalueerd tussen een breed scala van trillingsfrequenties en versnellingen, en de geïnduceerde spieractiviteit. Daarnaast werd de overdracht van het trillingssignaal door het menselijk lichaam beoordeeld en werd de veiligheid van de verschillende soorten lichaamsvibratietraining gemeten. In hoofdstuk 1 testten we de overdracht van trillingen van een trilplaat doorheen het lichaam tot aan het hoofd en werd de spieractiviteit van de onderste ledematen spieren gemeten. In hoofdstuk 2 werdeen nieuwe vibratietoestel getest, meerbepaald met een cable-pulley afweersysteem bevestigd aan een trilplaat, in een poging om de trillingen indirect van het platform naar het bovenlichaam te leiden om zo het effect van vibratietraining op de spieren van de bovenste ledematen te vergroten.

De belangrijkste bevindingen van beide studies toonden aan dat de versnellingen van het platform significant verminderen doorheen het lichaam tot aan het hoofd. De trillingen verhoogden de spieractiviteit in de meeste onderzochte spieren, maar gemiddeld werd geen duidelijke 'dosis-respons relatie' gevonden tussen de versnelling en/of de frequentie en spierreactie. Op basis van de resultaten van deze studies hebben we geconcludeerd dat de specifieke vibratieparameters die in dit proefschrift gebruikt werden, beschouwd kunnen worden als veilig en geschikt voor een vibratietrainingsprogramma.

In hoofdstuk 3 hebben we aan de hand van een gerandomiseerde gecontroleerde pilootstudie het effect van 6 weken WBV-training inpatiënten met een cerebrovasculair accident onderzocht, in een poging om de WBV-training in andere populaties dan enkel jongvolwassenen en ouderen toe te passen. Dit was de eerste studie die aantoonde dat specifieke intensieve WBV-training een veilige en haalbare manier is om de spierkracht van de onderste ledematen en posturale controle te verbeteren bij volwassenen met een hersenbloeding.

Tenslotte, in hoofdstuk 4 onderzochtenwe een andere vorm van vibratietraining, meerbepaaldlokale vibratietraining, om de invloed van vibratietraining op kwetsbare ouderen te verbeteren. Daarom werd lokale spiervibratie op de dij en rond de heup gedurende 6 maanden toegediend in een groep van postmenopauzale vrouwen. Dit was de eerste gerandomiseerde gecontroleerde pilootstudie die aantoonde dat specifieke lokale vibratietraining geschikt kan worden bevondenom een deel van de spierkracht van de onderste ledemanten bij postmenopauzale vrouwen te verhogen. Echter, de lokale vibratietraining had geen effect op botdensiteit, spiermassa en fysieke prestaties.

Samengevat, dit doctoraatsproject was het eerste dat verschillende methoden van vibratietraining heeft bestudeerd, meerbepaalde globale en lokale vibratietraining, met als doelde impact van vibratietraining in verschillende populaties te verbreden. De huidige bevindingen geven aan dat niet alleen gezonde volwassenen getraind kunnen worden, maar ook patiënten trainen met cerebrovasculair accident en postmenopauzale vrouwen. Wij concludeerden dat vibratietraining een haalbare en veilige trainingsmethode kan zijn om spierprestaties in verschillende populaties te vergroten.

Desondanks blijft het nog steeds onduidelijk wat het meest optimale vibratietrainingsprogramma is in termen van vibratieparameters (frequentie en amplitude), de duur van de blootstelling aan trillingen en de rusttijden, het aantal perioden per sessie, het aantal sessies per dag, het soort oefeningen etc.

APPOSITIONS

If we spend more time on health education, so that people learn to be responsible for their own health, we will not have to spend so much time and money on therapy and rehabilitation. Prevention is better than cure.

Successful research is a strong interaction between human, financial and time resources. Lack of one of them will ultimately fail your attempts to realize your research ideas in the best possible way.

Motivation of study participants to take part in a long-term clinical trial, is only the responsibility of the researcher. Each person requires an individual approach and the researcher is responsible to find and keep the balance between participant’s benefits and motivation, and researcher’s interests.

ABOUT THE AUTHOR

Ekaterina Tankisheva was born on December 28th 1983 in Sofia, Bulgaria. She graduated the National High School of Mathematics and Sciences, Sofia, Bulgaria. She studied medicine at the Faculty of Medicine, Medical University – Sofia. She successfully obtained her master degree in Medicine in December, 2008. On August 1st 2009, she started her pre-doctoral program at the Faculty of Kinesiology and Rehabilitation Sciences, Catholic University of Leuven (Belgium) under the supervision of Prof. Sabine Verschueren and Prof. Steven Boonen. She successfully defended her pre-doctoral project and continued working as a full-time doctoral student. Her work focused on the evaluation of different whole-body and local vibration protocols in different populations. During her doctoral project, she supervised master students.

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Tankisheva E, Jonkers I, Boonen S, Delecluse C, van Lenthe GH, Druyts H, Spaepen P, Verschueren SMP. Transmission of whole body vibration and its effect on muscle activation *J Strength Cond Res* 27(9): 2533 – 2541, 2013.

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Tankisheva E, Boonen S, Druyts H, Verschueren S (2013). Transmission of platform vibrations through cables and its effect on upper-body muscle activity. 18th annual Congress of the European College of Sport Science, ECSS Barcelona – Spain, 26 – 29 June 2013.

Appendix 1: Optimization of the vibration signal characteristics and application positions for local vibration

Vibrations delivered from the custom-made vibrators were transported through the soft tissue of the limb from the upper side of the skin till the bone structure. From mechanical (dynamical) point of view the soft tissue can be considered as an equivalent system of a damper and a spring (or more dampers/spring systems in series). That means that the original amplitude (and phase) of the vibrations on the skin surface are damped during transport through the soft tissue so that the resulting vibrations on the surface of the bone structure differs from amplitude (and phase) compared the original vibration. The parameters of the mechanical equivalent spring/damper system are depend of the "construction" of the limb of the subject (thickness, density and structure of skin, fat and muscles). So the real amplitude (and phase) that has effect on the bone structure is difficult to predict but it is perhaps predictable by calculations with finite element methods (FEA).

The first step in the development of local vibration therapy was to estimate the required magnitude of local loading that would generate enough mechanical stimulus for the bone to activate bone formation, and/or to slow down bone resorption. The femoral neck was chosen as target site because of its clinical relevance. *In silico* analyses were performed in which we compared local loading to the loading as induced by standing on a vibration platform (35 – 40 Hz, 2.28 – 5.09 *g*) that was shown to have a positive effect on bone adaptation[1]. Thus, a finite element model of a left female femur was constructed based on a CT scan. The mesh was built using Mimics and 3Matic (Materialise, Haasrode, Belgium) and consisted of over 83,000 four-nodded tetrahedral elements with an average element edge length of 6 mm. Bone material properties were assigned based on the local density as measured with CT, and were based on literature.[2]

The reference load case consisted of an axial loading of 700 N and was applied at the knee joint. The displacements at the hip (Fig. 1a, region C) were fully constrained. The average equivalent elastic strain was determined for the femoral neck (Fig. 1a, volume Y). To quantify the effect of positioning of a local vibration device, loads were independently applied to points D1, D2 and D3, respectively. To quantify the effect of orientation, two loading directions were used, one normal to the surface in the application point and one along the x-axis of the model (as indicated in Fig. 1a). For each load the average value of the equivalent elastic strain was computed for all elements in region Y and compared with the reference load case. The equivalent force as applied at the locations D1, D2 and D3 was determined such that the average strain in the femoral neck was identical to the strain induced by the reference loading.

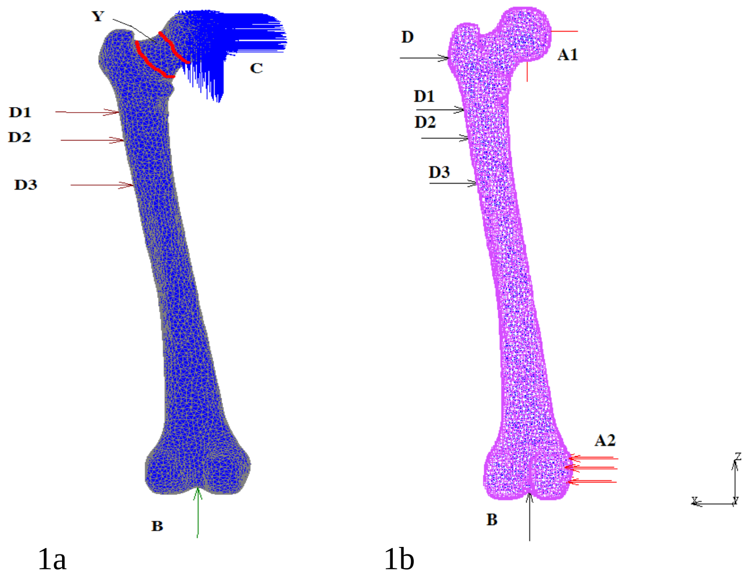


Figure 1. Two different boundary conditions were applied to a finite element model of a femur. **1a:** case 1, in which displacements at the head were fully constrained. **1b:** case 2, in which only the center of the head was fully constrained, allowing rotation to occur.
NOTE: B: load application for reference case; C: surface of the femoral head, constrained zero displacement in all directions; D1, D2, D3: selected regions for local load application; Y: femoral neck; A1: constrained zero displacement in all directions; A2: constrained displacement in X and Y direction.

The precise motion at the hip during WBV is not known. Slight movement may occur because of cartilage deformations and rotation of the hip. Therefore, in a second set of boundary conditions, we evaluated the effect of allowing relative motion at the femoral head. For that purpose, only the displacements at the center of the femoral head were constrained (Fig. 1b), allowing rotation to occur. In order to prevent rotation of the entire femur, the x and y displacement of the medial condyle were constrained in x-, and y-direction.

For the reference case the entire bone was strained and relatively high strains were found in the femoral neck (Fig. 2). These analyses also showed that equivalent loading was lowest at location D1, and that they increased with increasing distance to the femoral neck (Table 1). Furthermore, these analyses showed that loading normal to the surface of the bone required higher load magnitudes than when loading was applied in x-direction. The difference was

10.9% at location D1 and reduced to only 1.9% at location D3 demonstrating that when loading is applied closer to the femoral neck, the effects of loading direction are reduced.

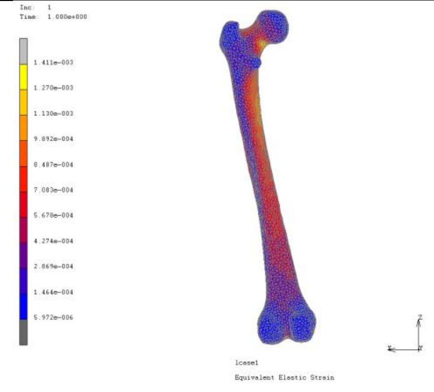
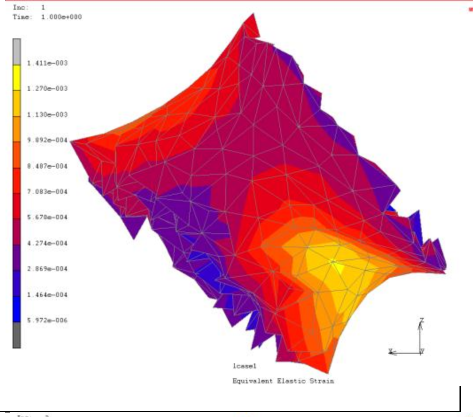
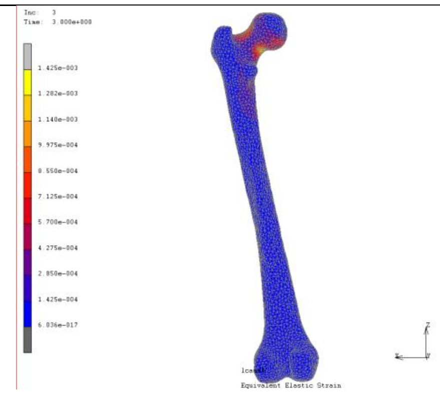
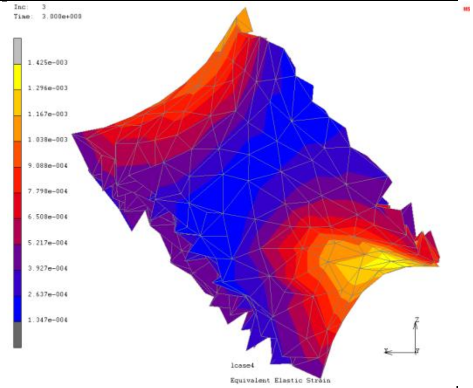
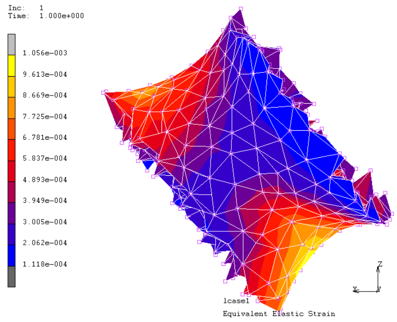
	Femur	Femoral neck
Reference Load case 1 - F = 700 N		
- D3 - Orientation X - F = 157 N		

Figure 2: Strain distribution in the femur and in the femoral neck for the reference load case and for the case in which load was applied at location D3.

	Load direction	
Location	x-direction	Normal to surface
D1	338	375
D2	234	250
D3	157	160

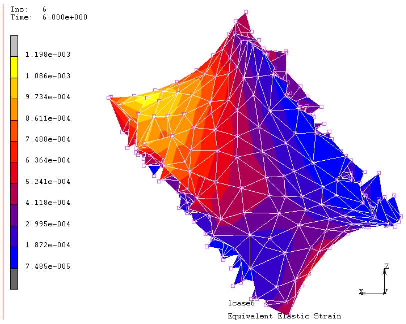
Table 1: Loads [N] at location D1, D2, and D3, respectively, that resulted in an identical average equivalent elastic strain as in the reference case.

For case 2 in which the displacement was constrained at the center of the femoral neck only, the average equivalent elastic strain was 0.0395%. This was lower than for case 1 which was expected because of the increased flexibility as induced at the hip. The loads as applied to locations D, D1, D2, and D3, respectively, were higher than for case 1. Again, equivalent loads were lowest when load was applied close the femoral neck (Fig. 3). As for case 1, the analyses demonstrated that local vibrational loading could result in similar bone strains as experienced during WBV. Moreover, the strains at the superior side of the neck were higher for local vibrational loading.



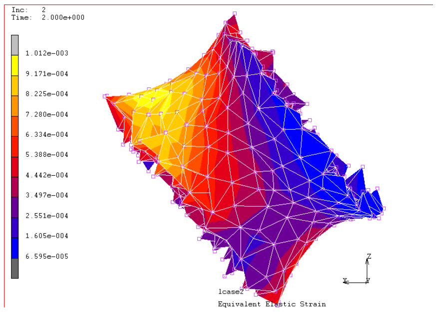
Reference case

F = 700N



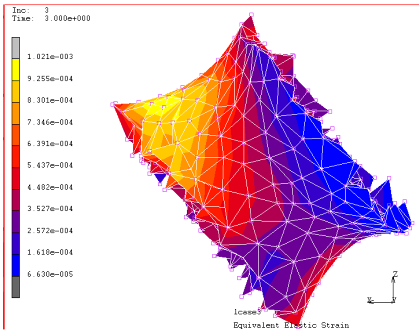
Application side: D

F = 756.9N



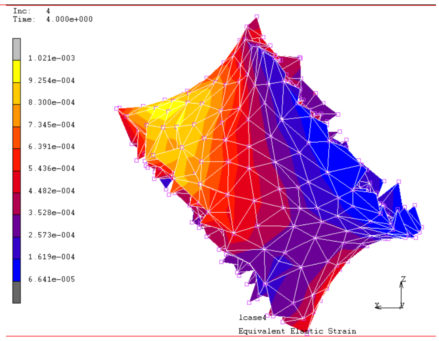
Application side: D1

F = 857.8N



Application side: D2

F = 965.5N



Application side: D3

F = 1192.4N

Figure 3: Strain distribution in the femoral neck for the reference load case and for the case in which load was applied to locations at the proximal femur, locations D, D1, D2, and D3, respectively.

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Acknowledgement

Finite Element Analysis was performed with the collaboration of Prof. Harry van Lenthe.